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Probabilistic Wind and Power Predictions and Wind Resource Assessment with an Analog Ensemble

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  - Vattenfall
  - Vestas Wind Systems
  - Xcel Energy

Outline

- Analog Ensemble (AnEn) basic idea
- AnEn for short-term (i.e., 0-48 h) weather predictions
- AnEn for short-term (i.e., 0-72 h) power predictions
- AnEn for long-term (i.e., multi-year) wind resource assessment
- Summary and future work

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Weather analogs: basic idea

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Today

Weather analogs: basic idea

Today

One week ago?

Weather analogs: basic idea

Today

One week ago?

5 years ago?!?

Weather analogs: basic idea

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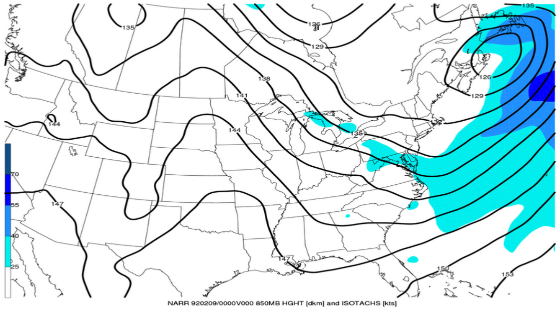

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One week ago?

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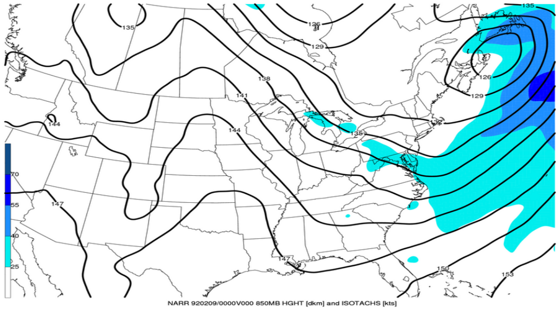
Weather analogs: basic idea



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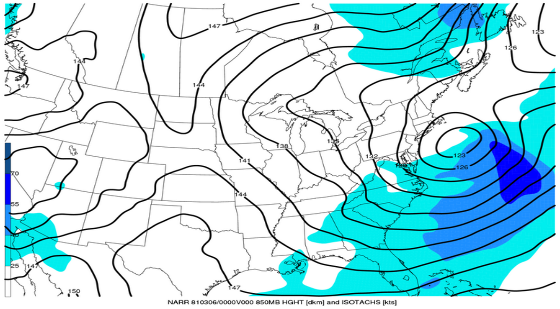

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Weather analogs: basic idea

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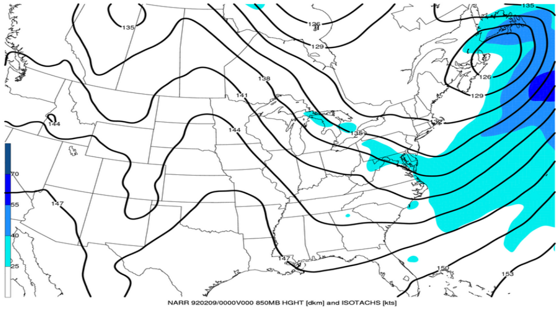

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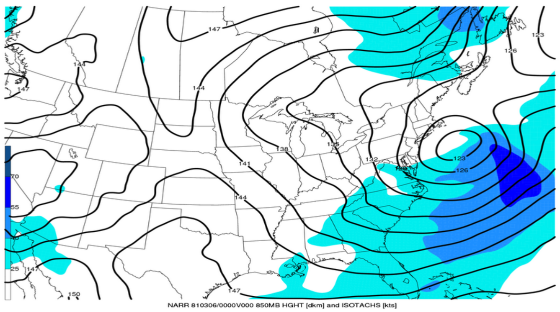
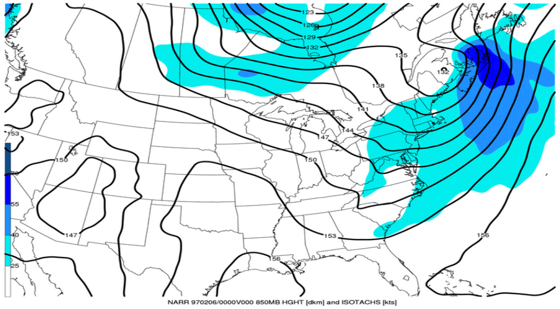


One week ago?



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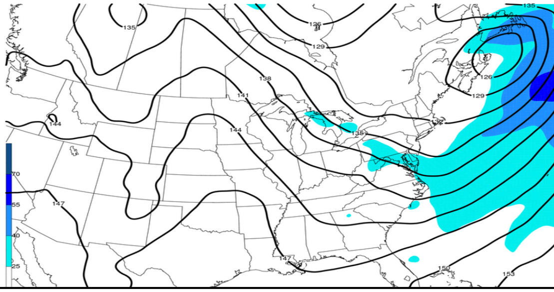
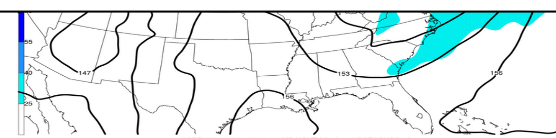
Weather analogs: basic idea



Can we use this information
(i.e., both obs and re-analysis),
to improve forecasts or resource estimates?



5 years ago?!?

There is a problem…

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Edward Lorenz, “Atmospheric predictability as revealed by naturally occurring analogues” (JAS 1969):

…

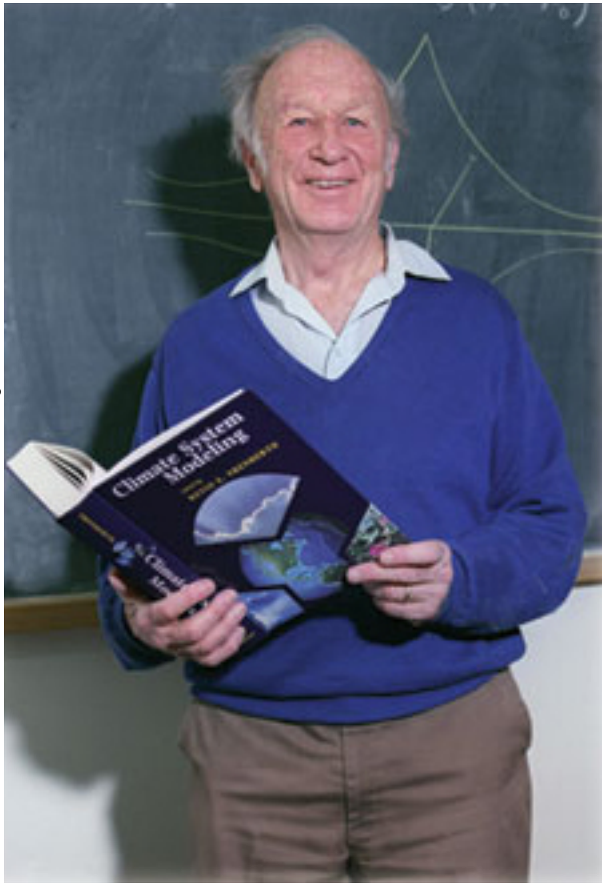
Five years of twice-daily height values of the 200-, 500-, and 850-mb surfaces at a grid of 1003 points over the Northern Hemisphere

…

There are numerous mediocre analogues but no truly good ones.

…

The likelihood of encountering any truly good analogues by processing all existing upper-level data appears to be small.



A possible solution?

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Huug van den Dool, “Searching for analogues, how long must we wait?” (Tellus 1994):

…

It is found that it would take a library of order of 10^{30} years to find 2 observed flows that match to within current observational error over a large area such as the Northern Hemisphere.

…

Obviously, with 10-100 years of data, the probability of finding natural analogous is very small, unless one is satisfied with analogy over small areas or in just 2 or 3 degrees of freedom

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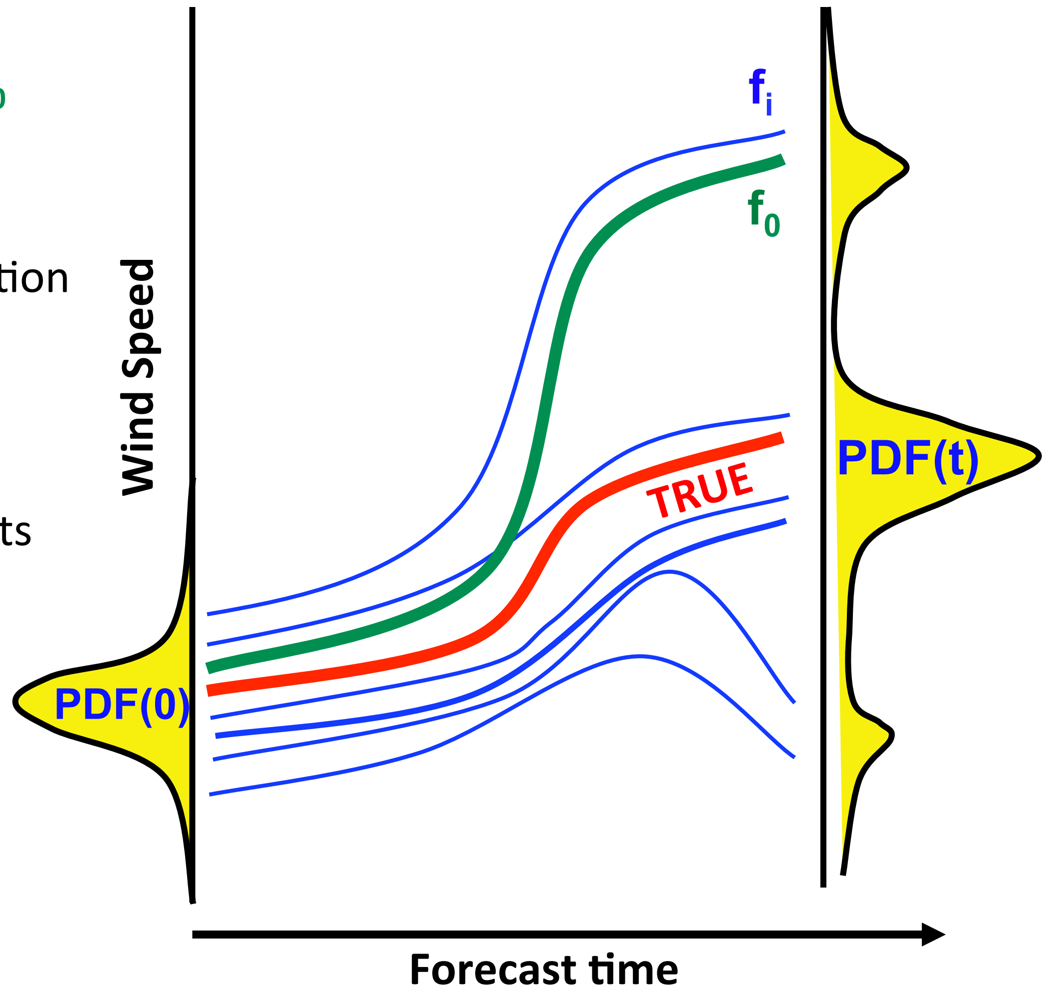
Ensemble Prediction

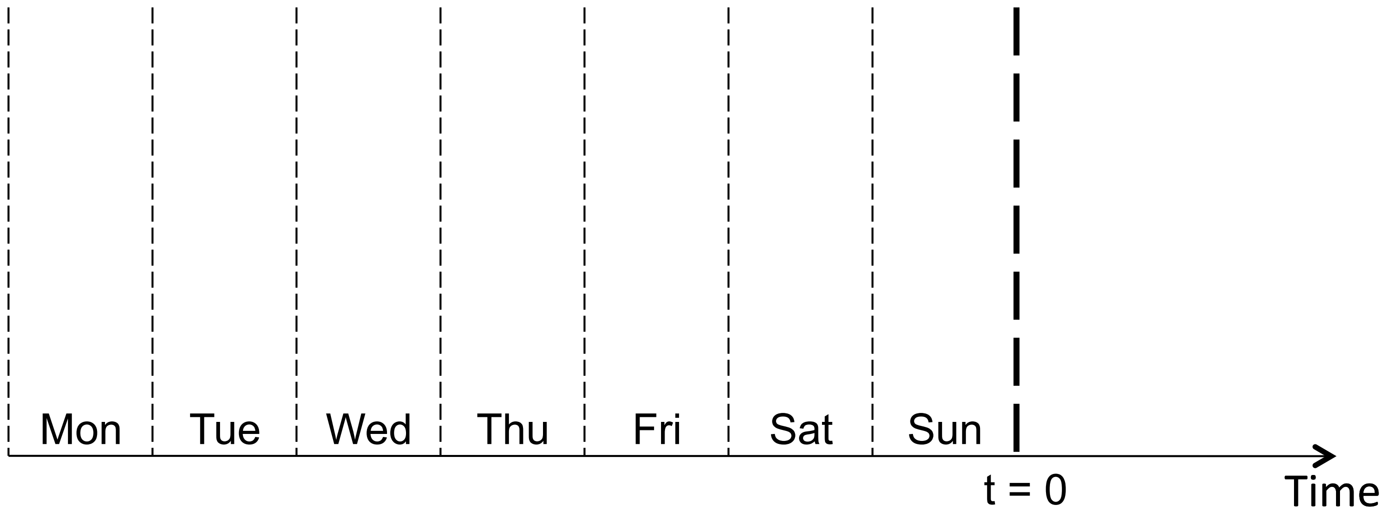
The single deterministic forecast **f_0** fails to predict the **TRUE**

The initial probability density function **PDF(0)** represents the initial uncertainties

An ensemble of perturbed forecasts **f_i**, starting from perturbed initial conditions designed to sample the initial uncertainties can be used to estimate the probability of future states **PDF(t)**



Analog Ensemble (AnEn)



Analog search as in Delle Monache et al. (MWR 2011)

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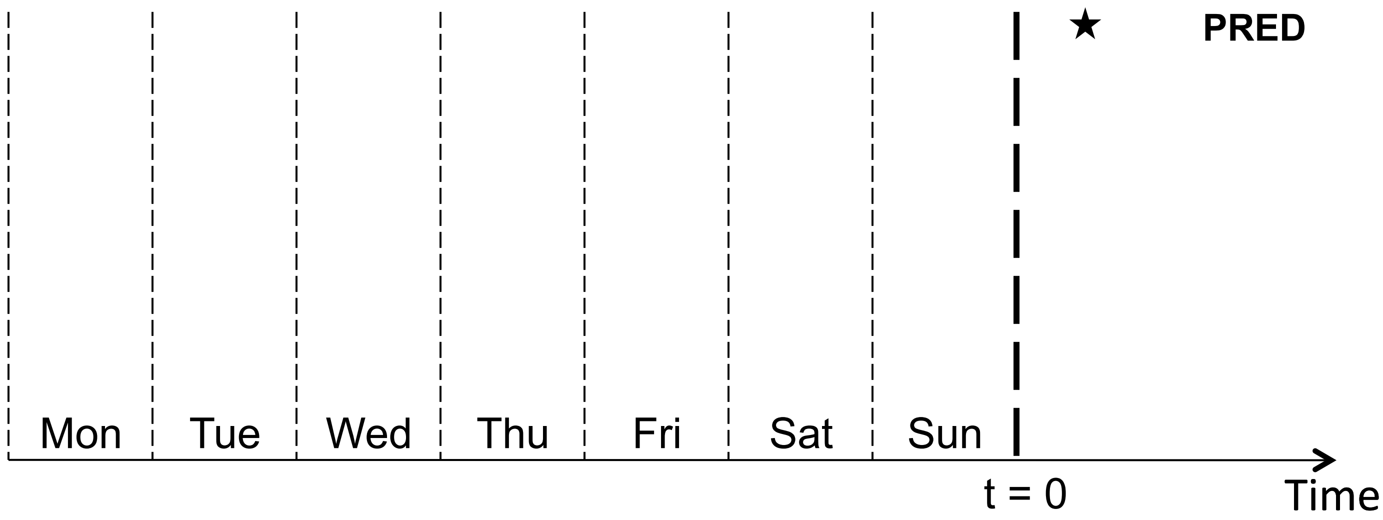

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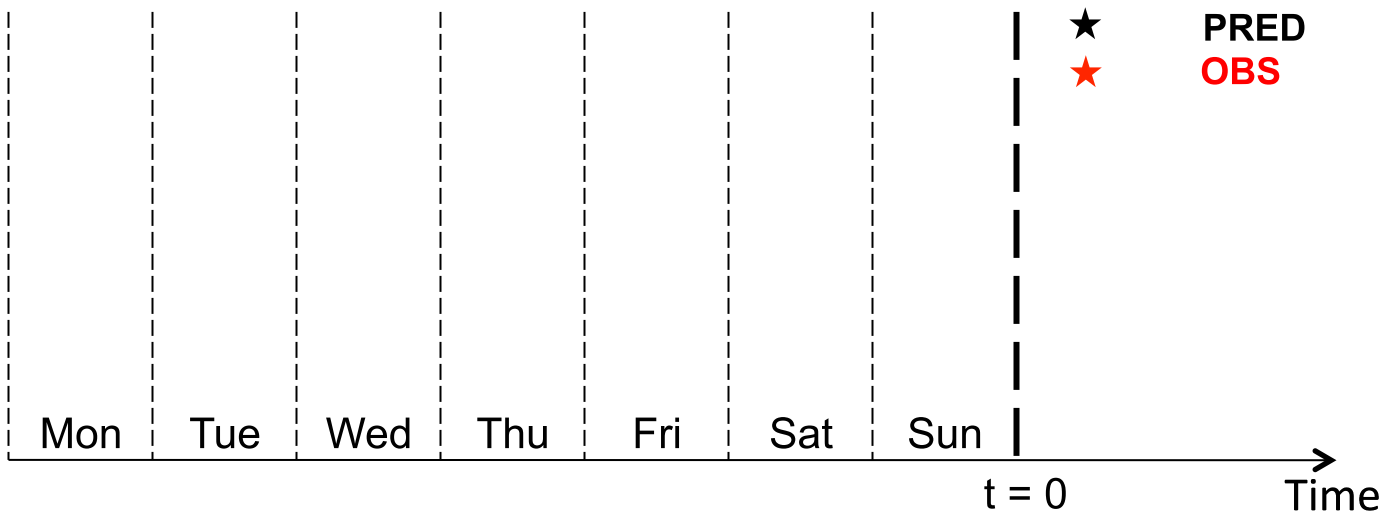

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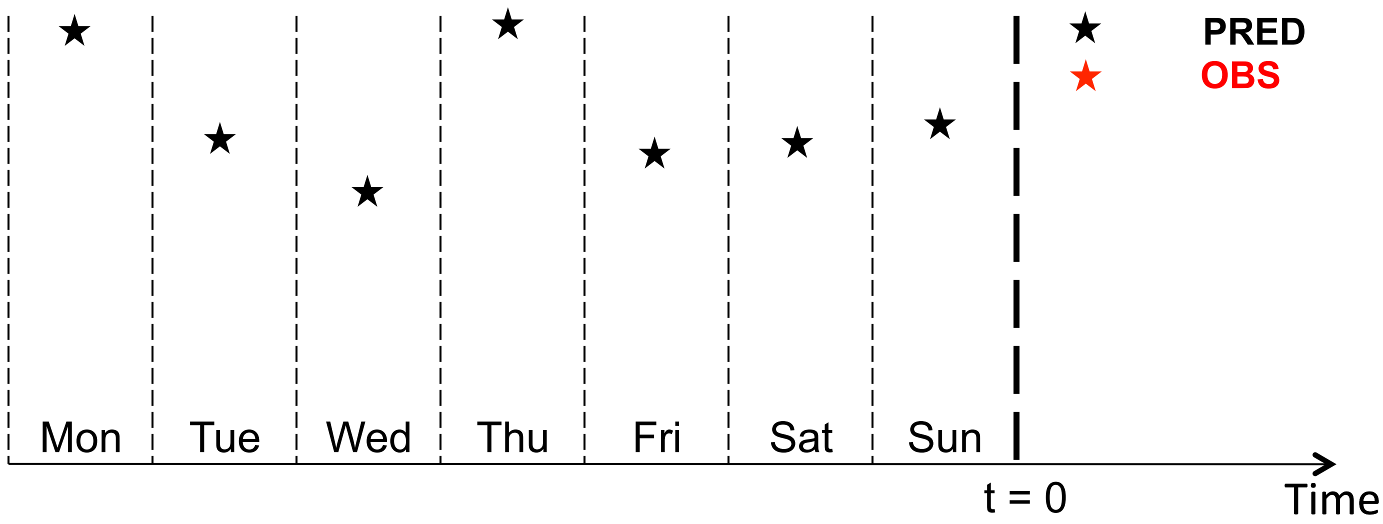

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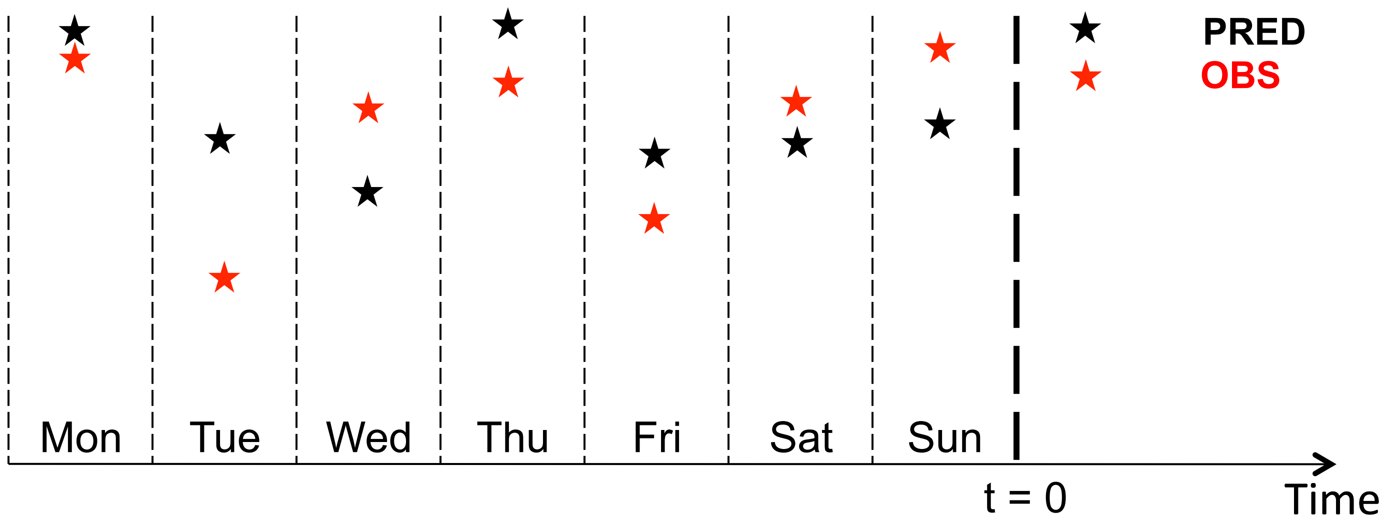

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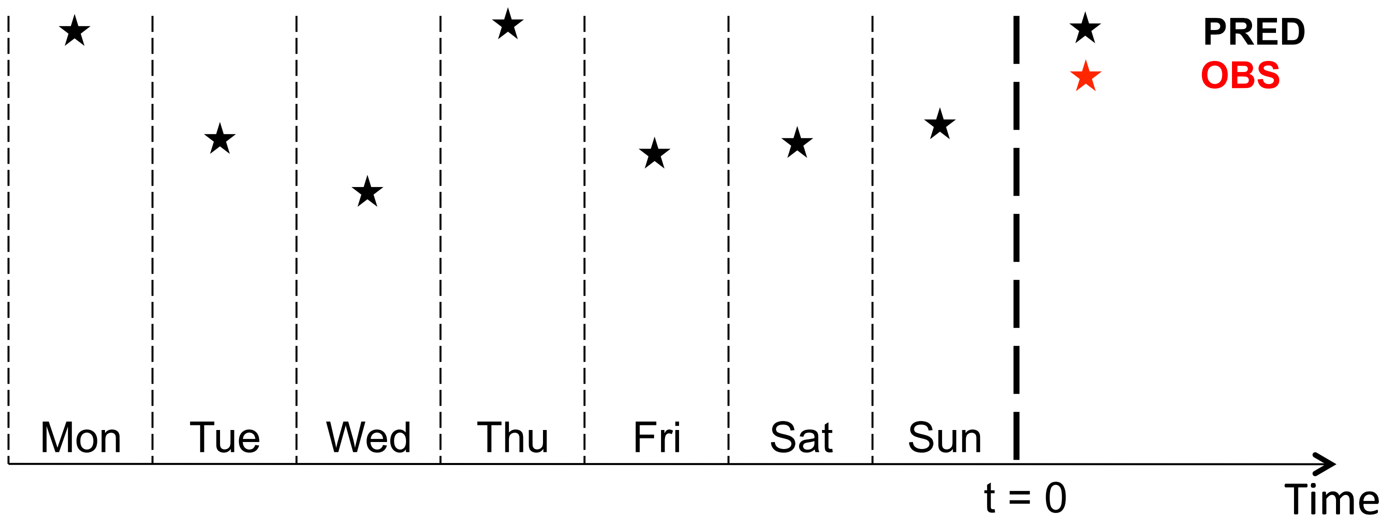

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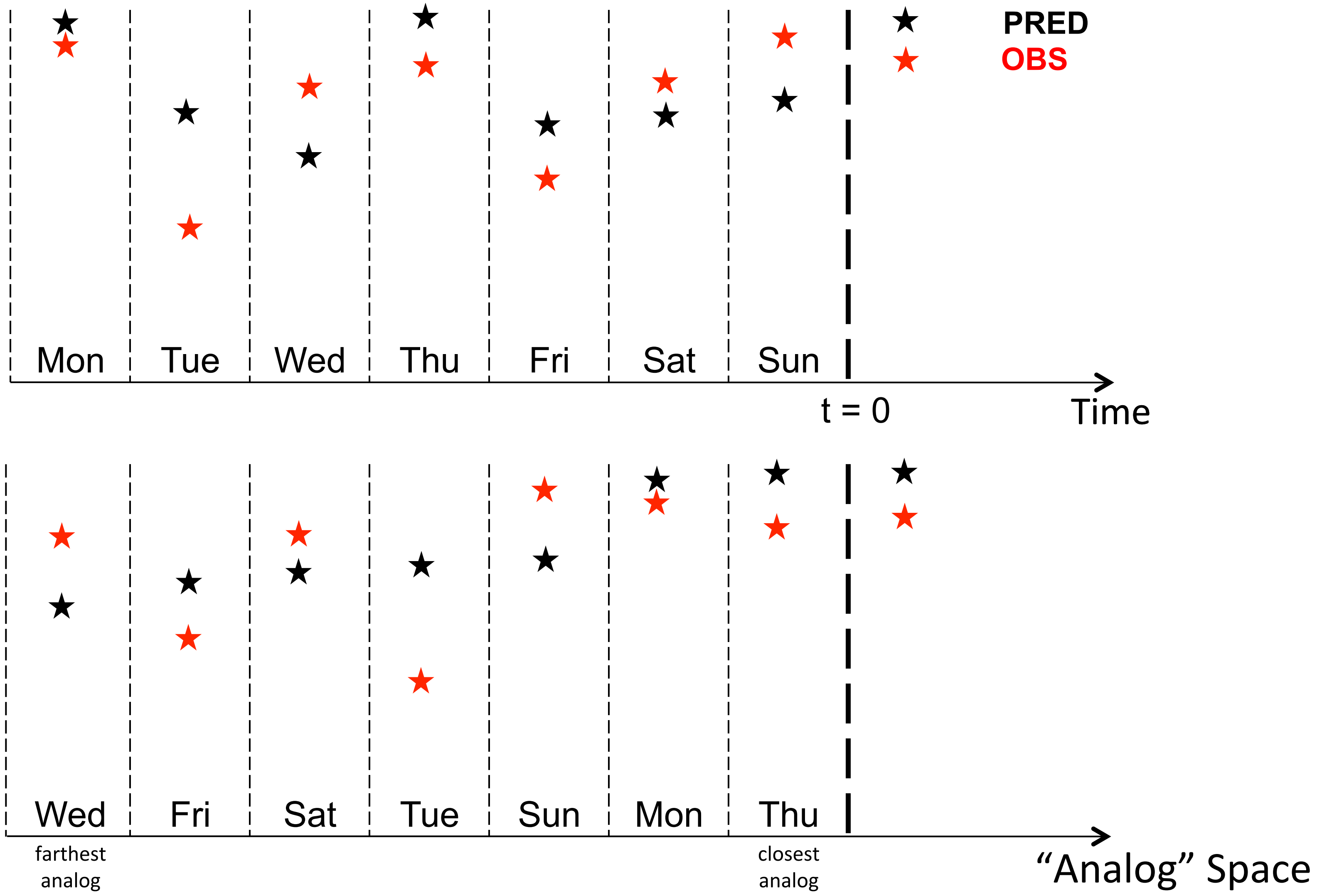

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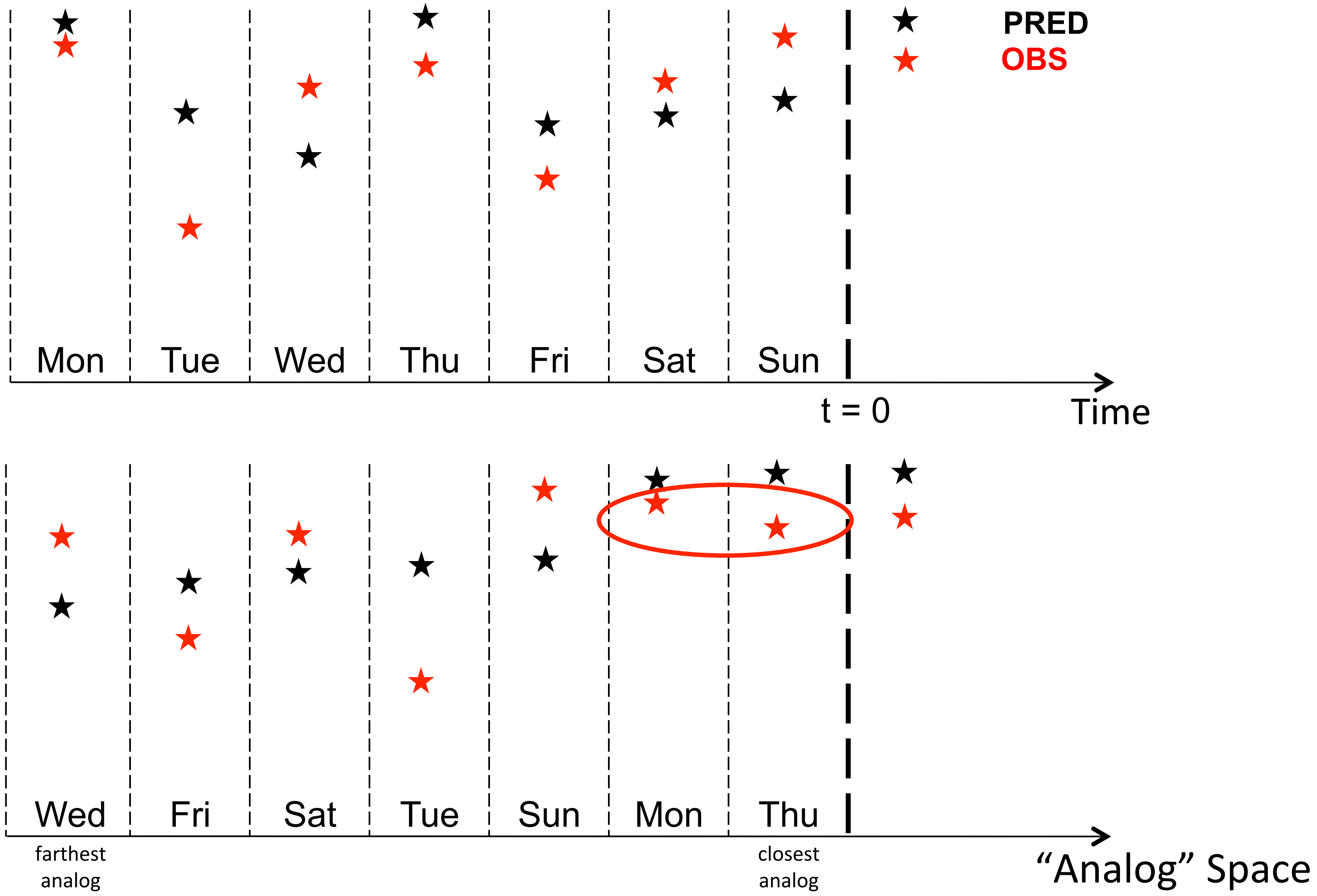

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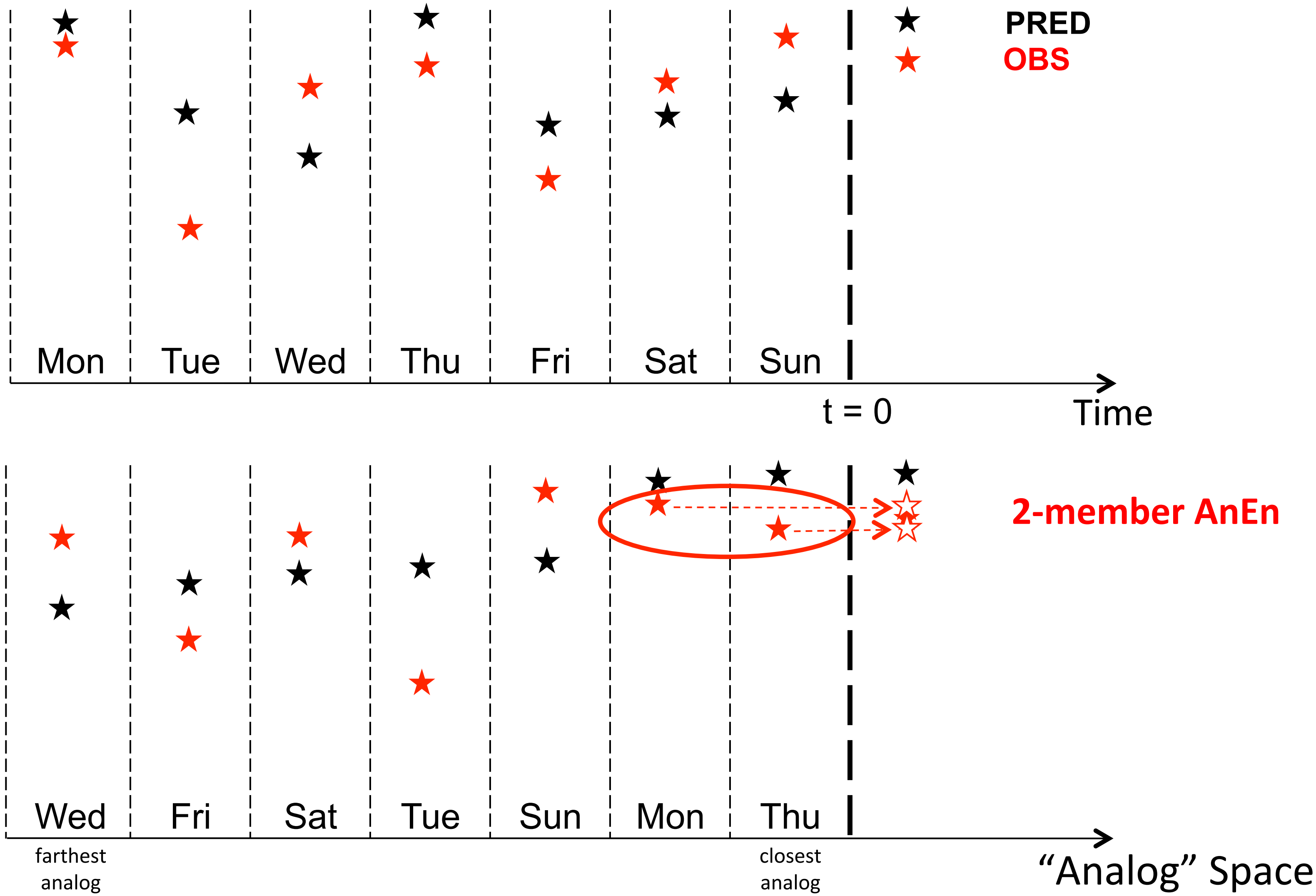

Analog search as in Delle Monache et al. (MWR 2011)

How skillful is AnEn?

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- AnEn generated with Environment Canada GEM (15 km), 0-48 hours
- Comparison with:
  - Environment Canada Regional Ensemble Prediction System (REPS, next slide)
  - Logistic Regression (LR) out of 15-km GEM
  - LR our of REPS, i.e., Ensemble Model Output Statistics (EMOS)
- Period of 15 months (verification over the last 3 months)
- 10-m wind speed
- 550 surface stations over CONUS (in two slides)
- Probabilistic prediction attributes: statistical consistency, reliability, sharpness, resolution, spread-error consistency

Regional Ensemble Prediction System (REPS)

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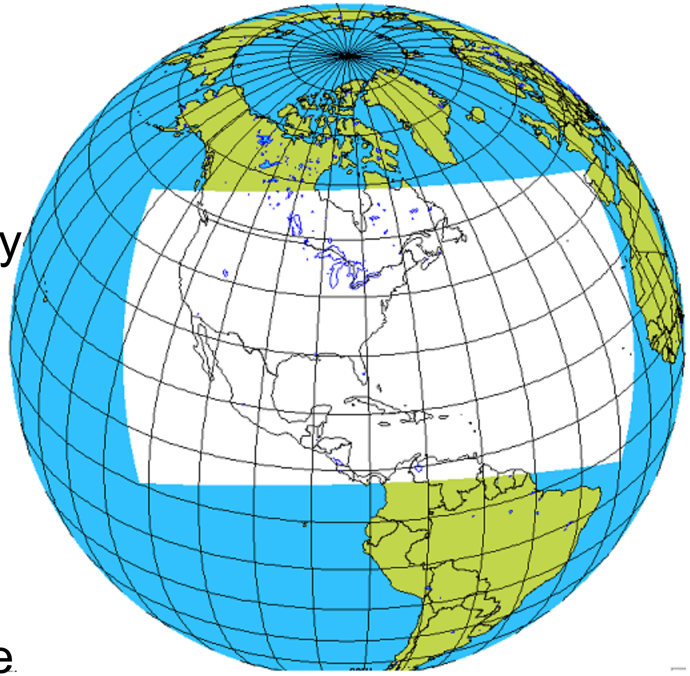
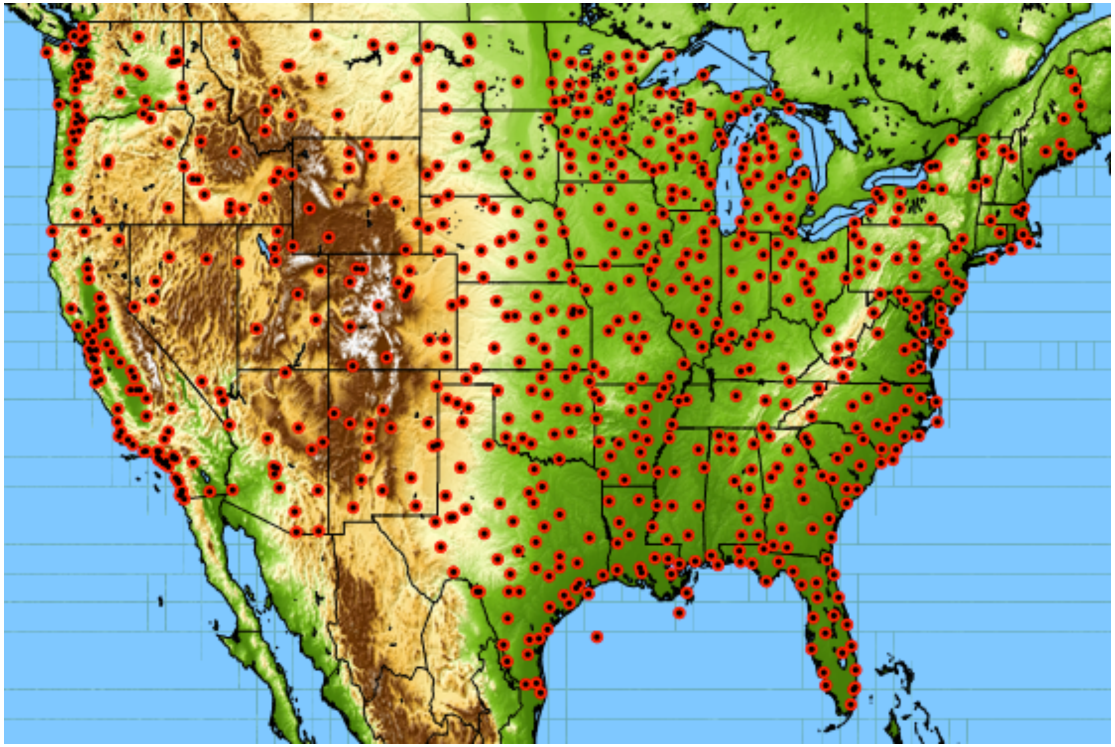
- Model: GEM 4.2.0 (vertical staggering)
- 20 members + 1 control run
- 72 hours forecast lead time
- Resolution: ~33 km with 28 levels
- Initial conditions (i.e., cold start) and 3-hourly boundary condition updates from GEPS (EnKF + multi-physics)
- Physics:
  - Kain et Fritsch (1993) for deep convection
  - Li et Barker (2005) for the radiation
  - ISBA scheme (Noilhan et Planton, 1989) for surface
- Stochastic Physics: Markov Chains on physical tendencies



Ground truth dataset

- 550 hourly METAR Surface Observations
- 1 May 2010 – 31 July 2011, for a total of 457 days
- 10-m wind speed



Probabilistic forecast attributes: Reliability

Example:

① An event (e.g., wind speed > 5 m/s) is predicted to happen with a 30% probability

② We collect the observations that verified every time we made the prediction in ①

③ If the frequency of the event in the observation collected is 30%, then the forecast is perfectly *RELIABLE*

Analysis of reliability & sharpness

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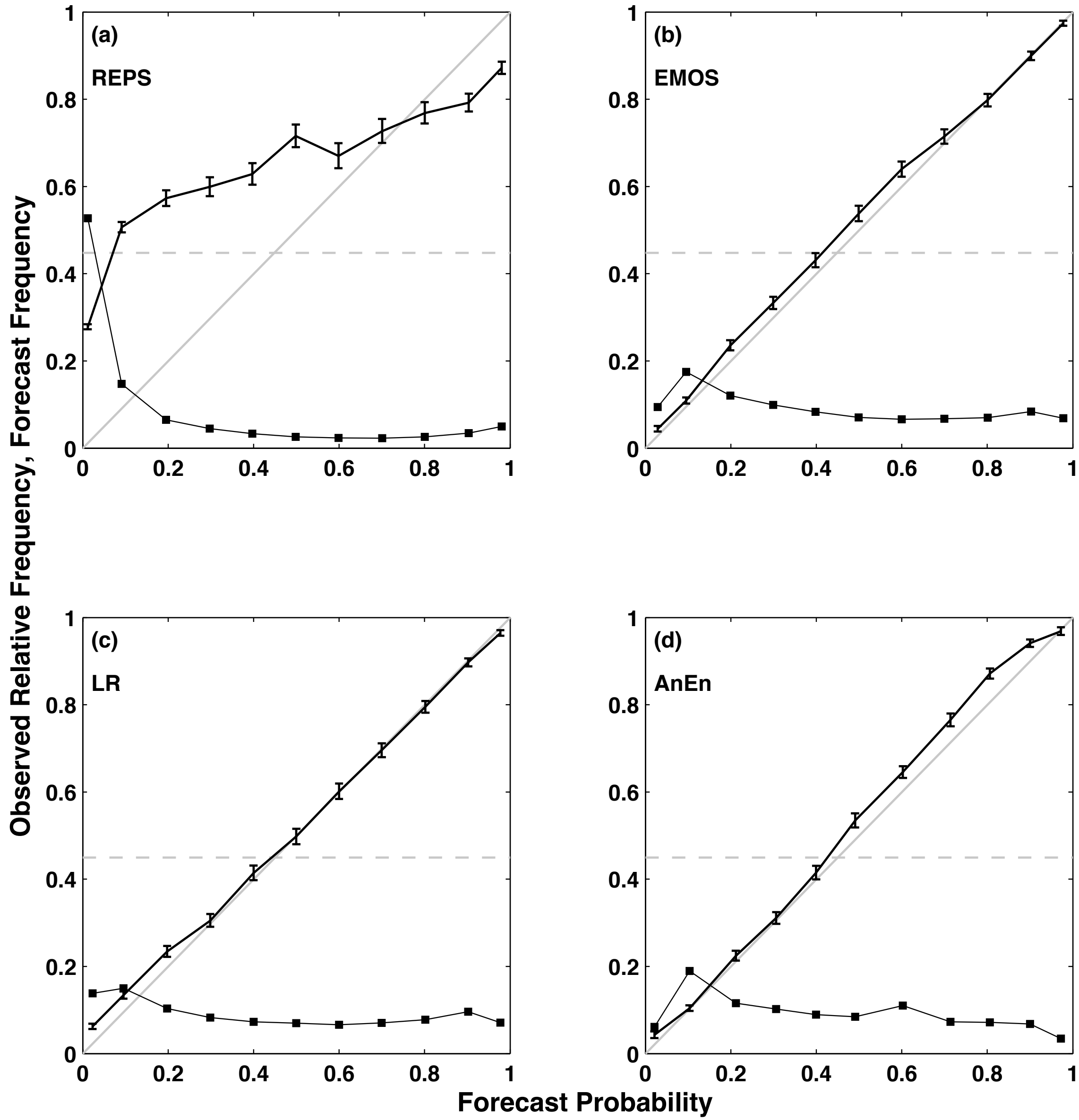
Reliability and sharpness diagram: 10-m wind speed > 5 m s^{-1}, 9-h fcst



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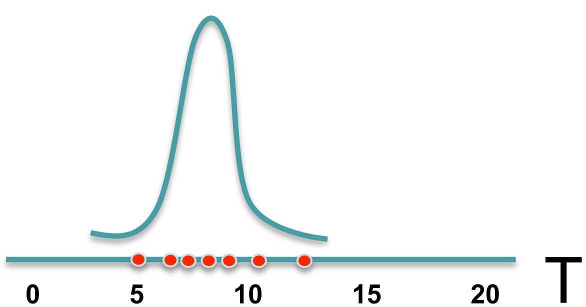
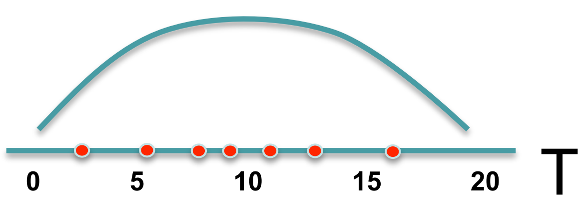
Probabilistic forecast attributes: Sharpness

Sharpness refers to the degree of concentration of a forecast PDF's probability density, and is a property of the forecasts only.

Ideally, we want the forecast system, while mainly reliable, with as many forecasts as possible close to 0% and 100%, corresponding to a perfect deterministic forecast system. However, an improvement in sharpness does not necessarily mean that the forecast system has improved.



Sharper Forecast



Less Sharp Forecast

Analysis of reliability & sharpness

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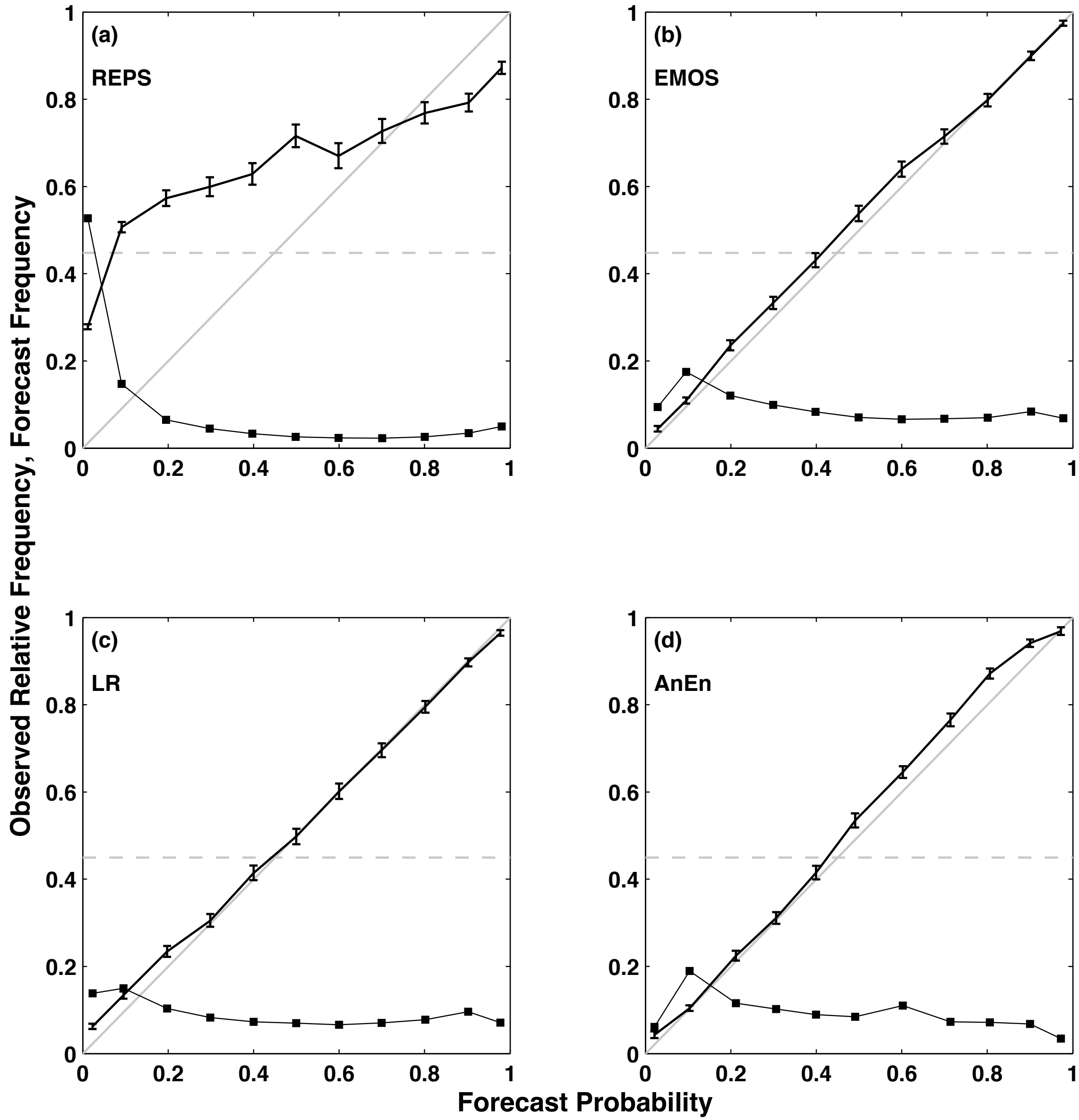
Reliability and sharpness diagram: 10-m wind speed > 5 m s^{-1}, 9-h fcst



Probabilistic forecast attributes: Resolution

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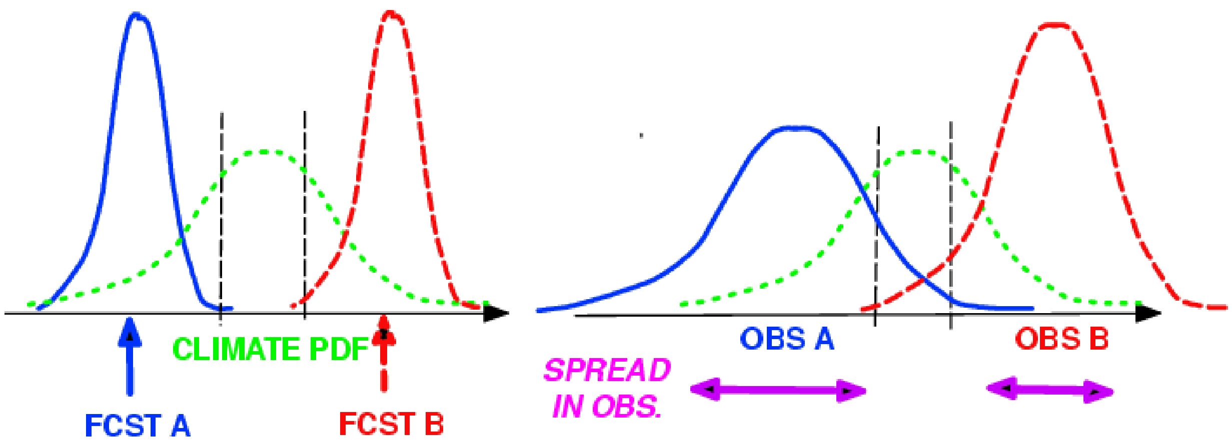

Consider different classes of forecast events.

If all observed classes corresponds to different forecast classes, then the probabilistic forecast has perfect *RESOLUTION*.

Analysis of Resolution (1)

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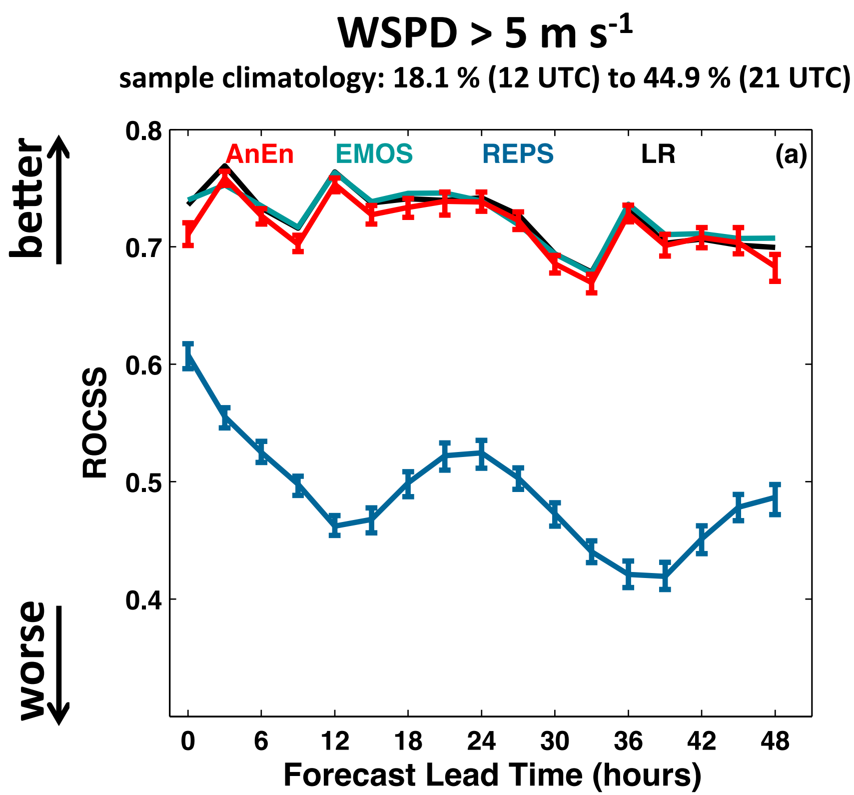
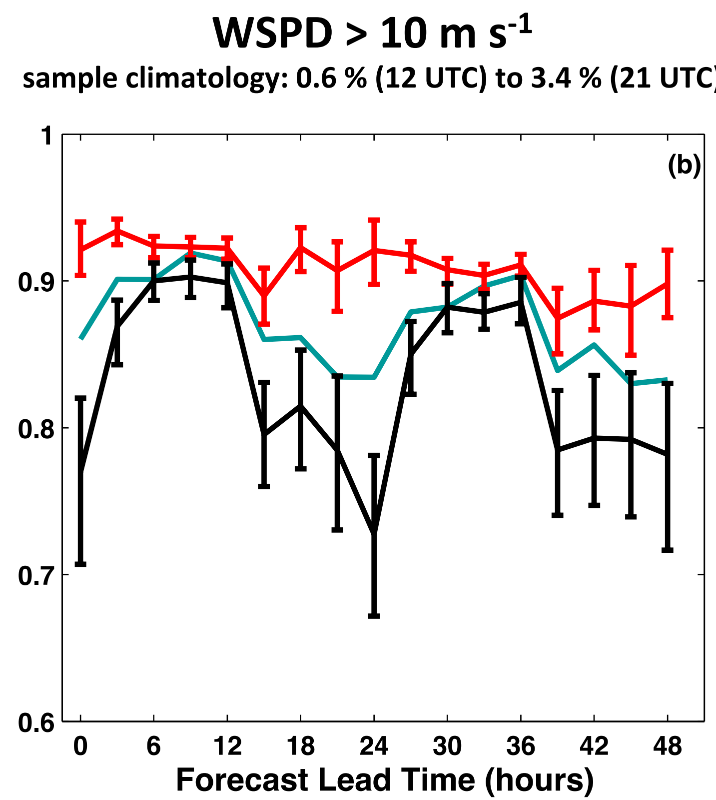
Relative Operating Characteristics skill score, 10-m wind speed ≥ 5, 10 m s^{-1}

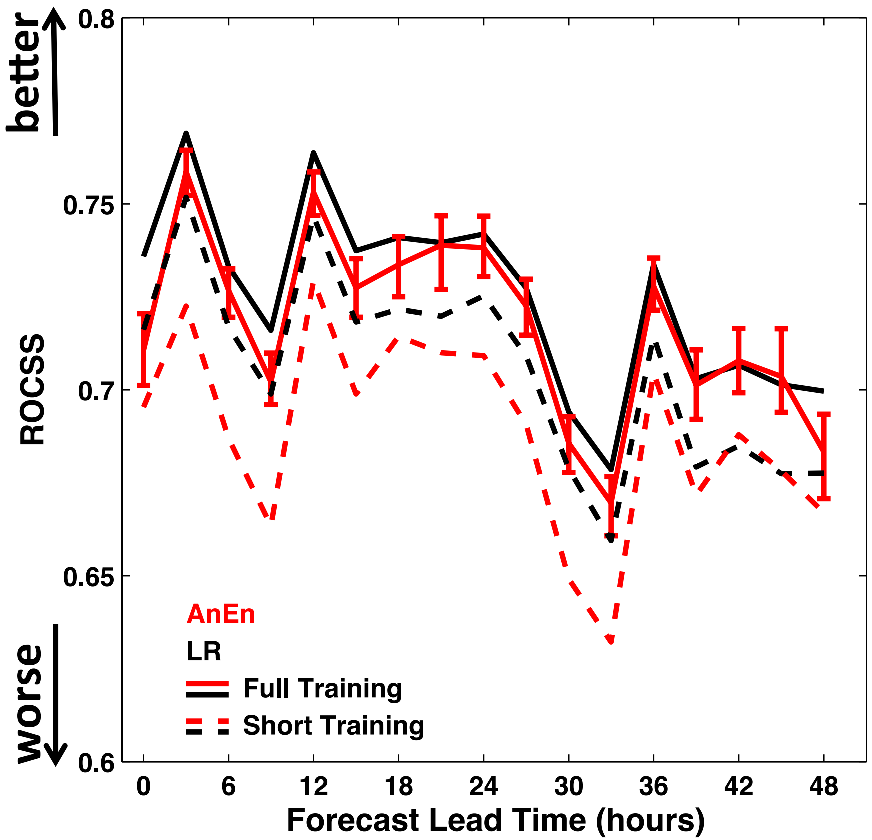




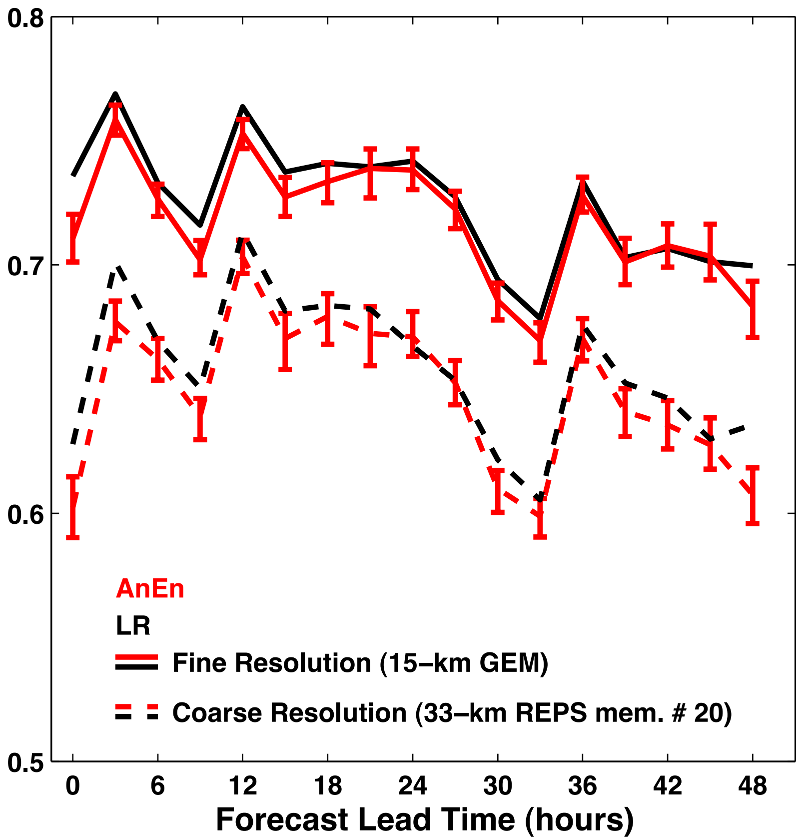
AnEn sensitivity

Relative Operating Characteristics skill score, 10-m wind speed ≥ 5 m s^{-1}

AnEn with a shorter training data set (15 → 9 months)



AnEn built with a coarser dynamical model (15 → 33 km)



Probabilistic forecast attributes: Statistical and spread-error consistency

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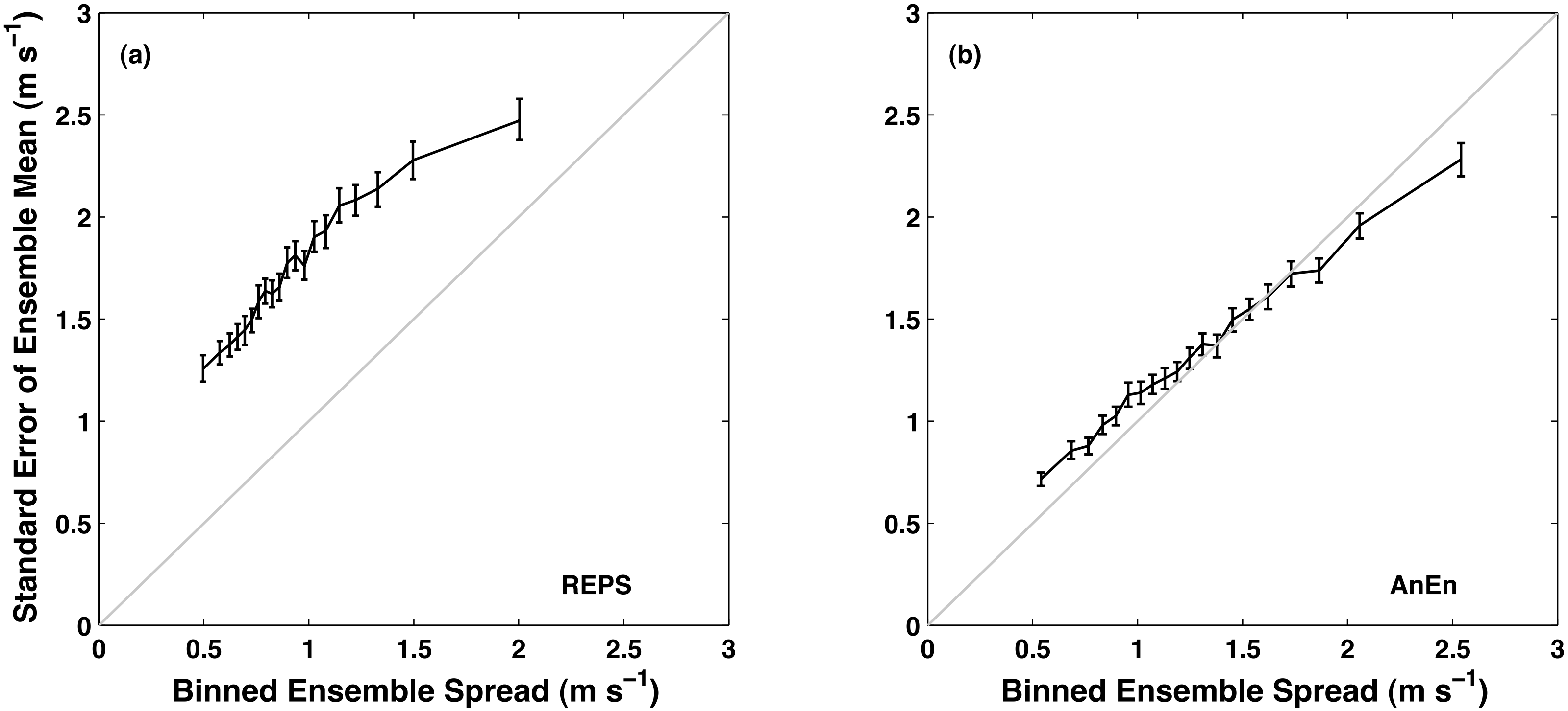
① The ensemble spread tell us how uncertain a forecast is. Ideally, large spread should be associate with larger uncertainties, low spread should indicate higher accuracy

② If an ensemble is perfect, than the observations are indistinguishable from the ensemble members

Analysis of spread-error consistency (2)

Binned spread-skill diagram, 10-m wind speed, 42-h fcst



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Probabilistic power prediction with an analog ensemble

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Goal:

Accurate power forecasts and reliable quantification of forecast uncertainty

Motivation:

- Increase wind energy penetration in the energy market
  - Optimized Servicing
  - Less spinning reserves needed and optimized servicing of wind individual turbines

Power predictions: Experiment design

- Test site: Wind farm in northern Sicily − 9 turbines, 850 kW Nominal Power (NP)
- Training period: November 2010 - October 2012
- Verification period: November 2011 – October 2012
- Probabilistic prediction systems: ECMWF EPS, COSMO LEPS, AnEn

Power predictions

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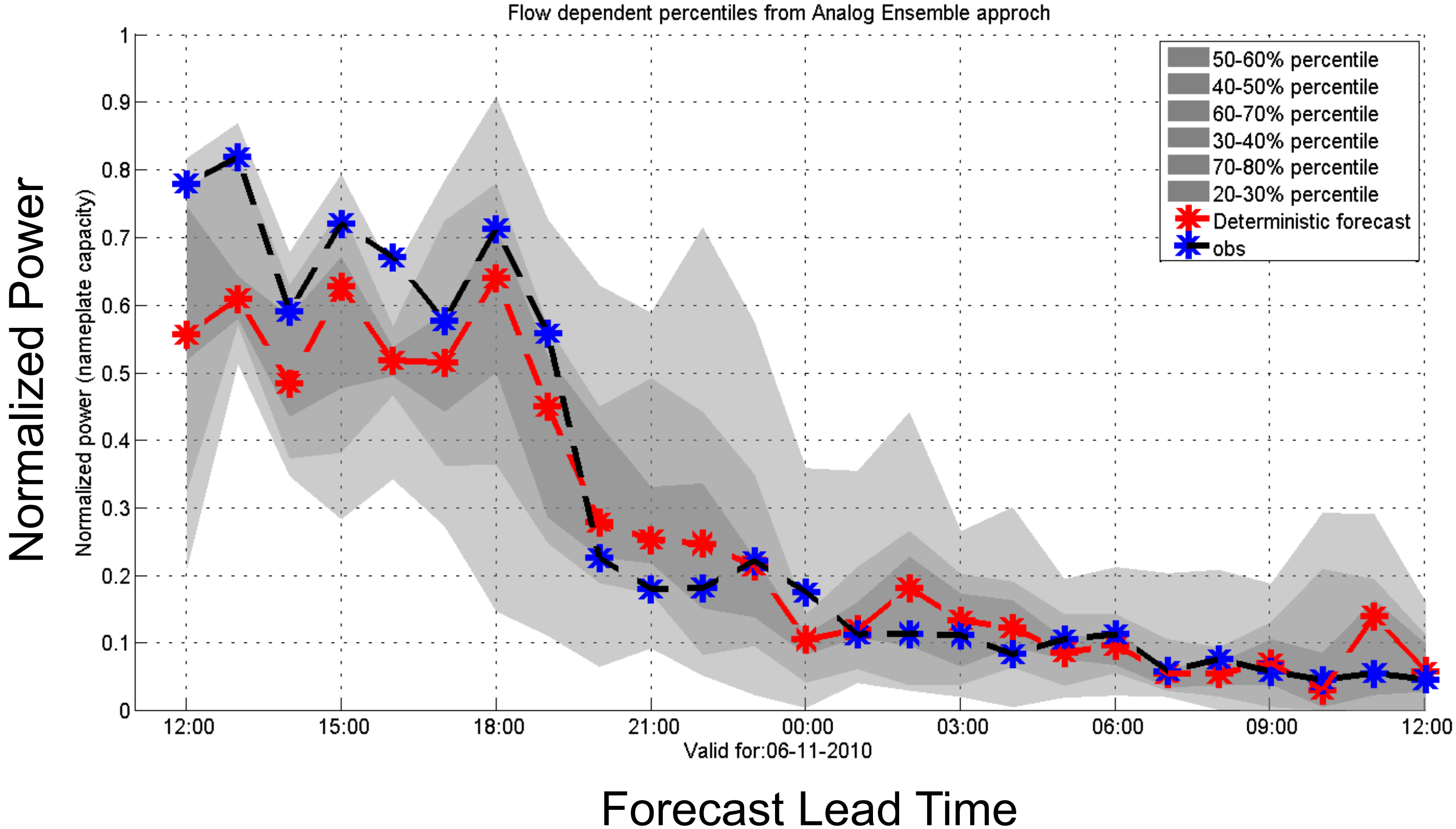
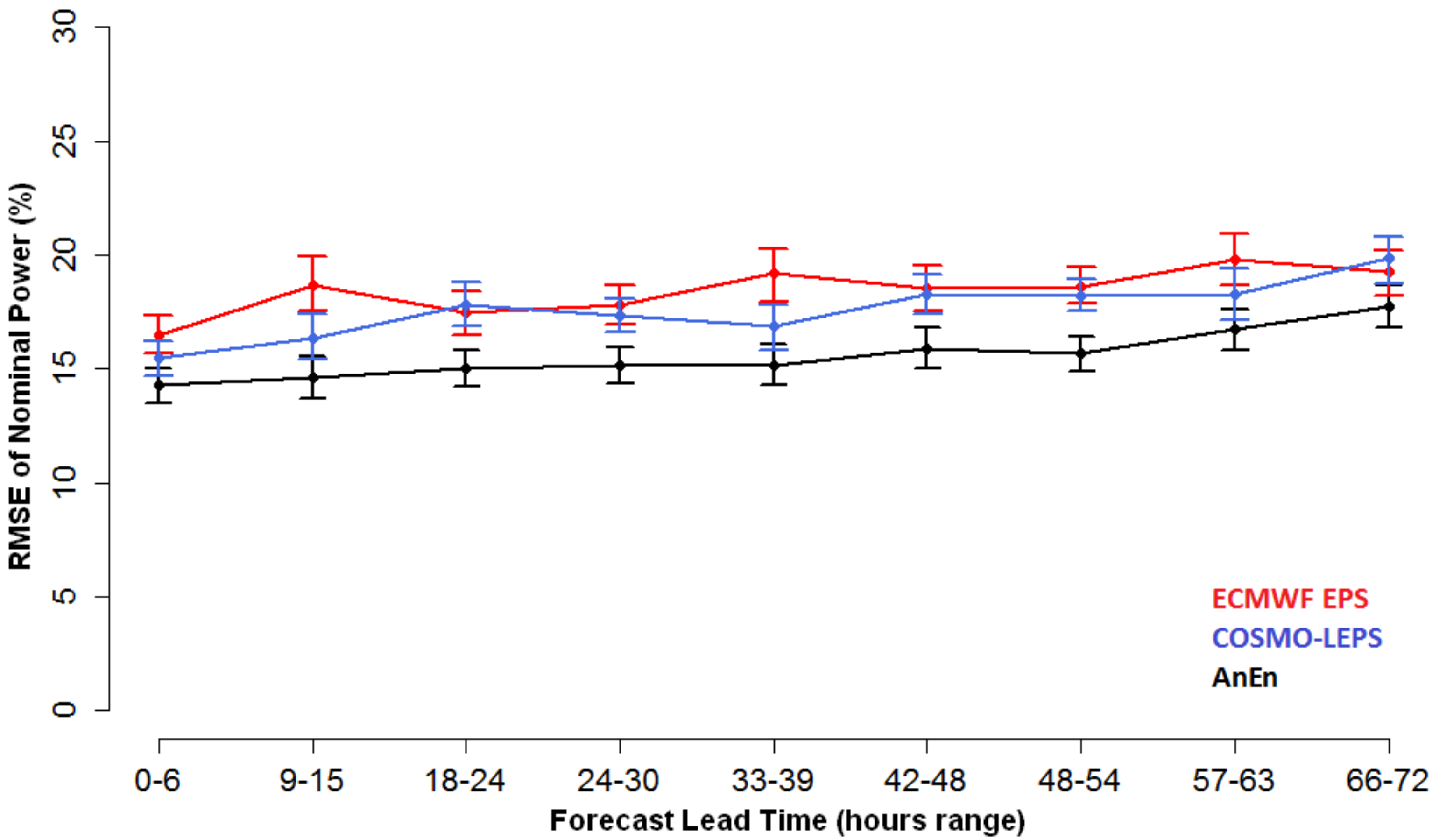


RMSE of ensemble means



Spread-skill relathionship

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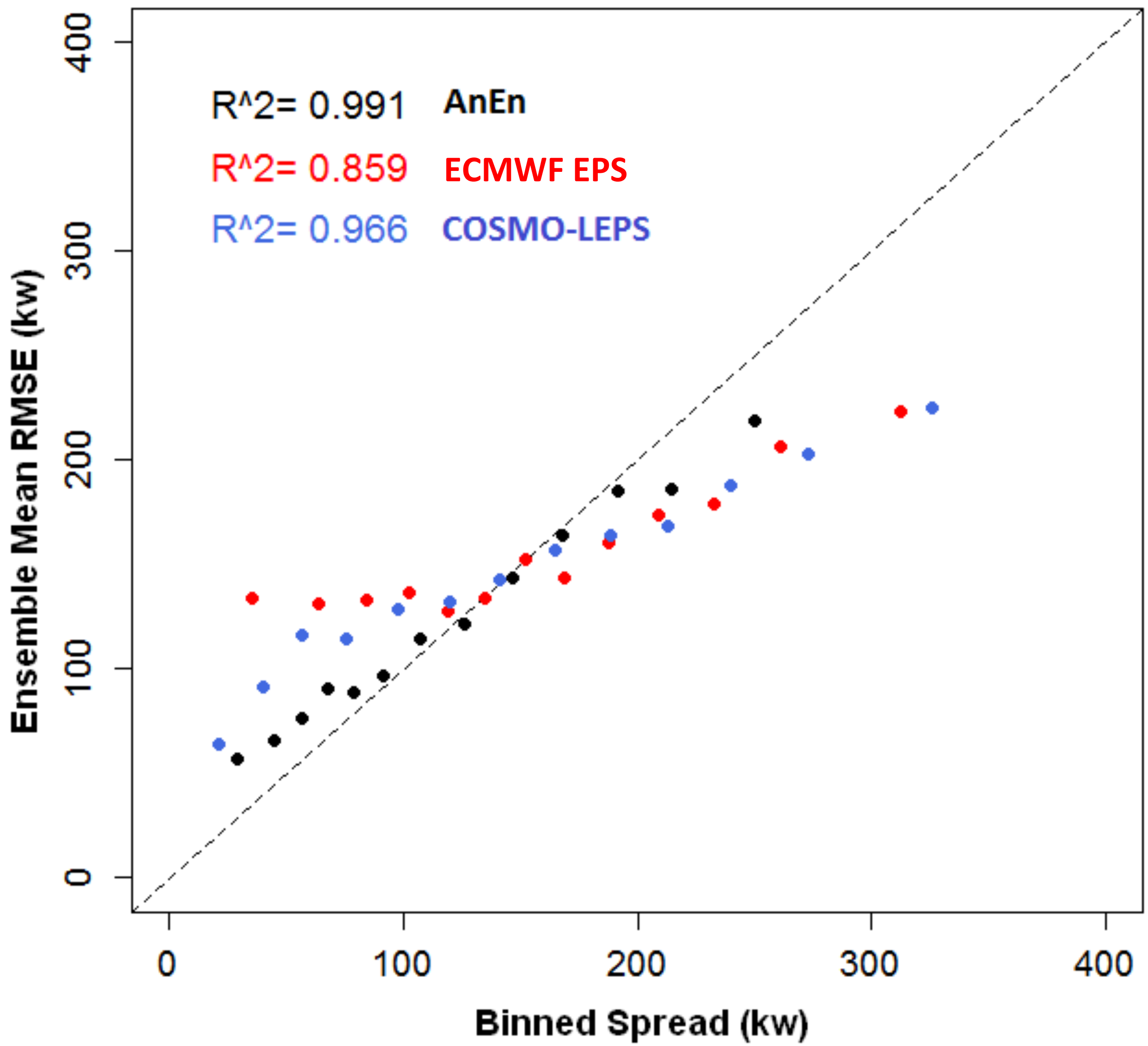

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AnEn for wind resource assessment

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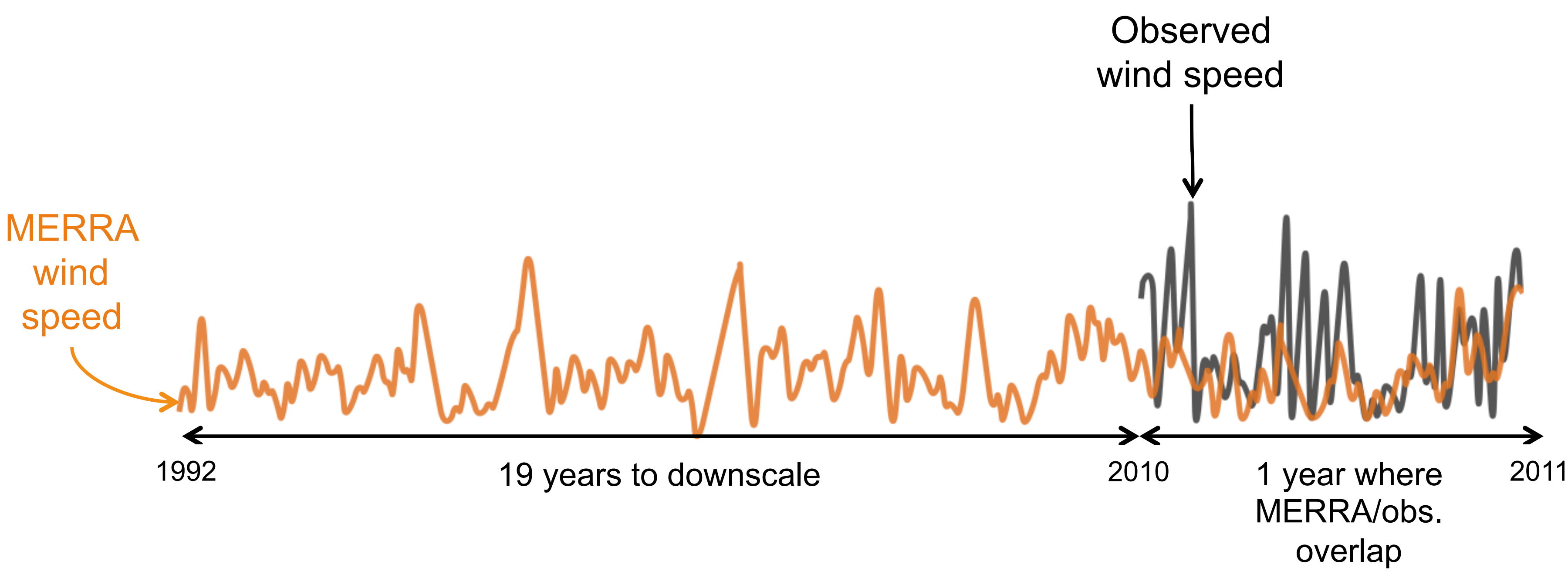
- Recreate a long-term observation-based wind climatology at site
- Downscale a long-term NASA Modern-Era Retrospective Analysis for Research and Applications (MERRA) time series using a short-term record of observations



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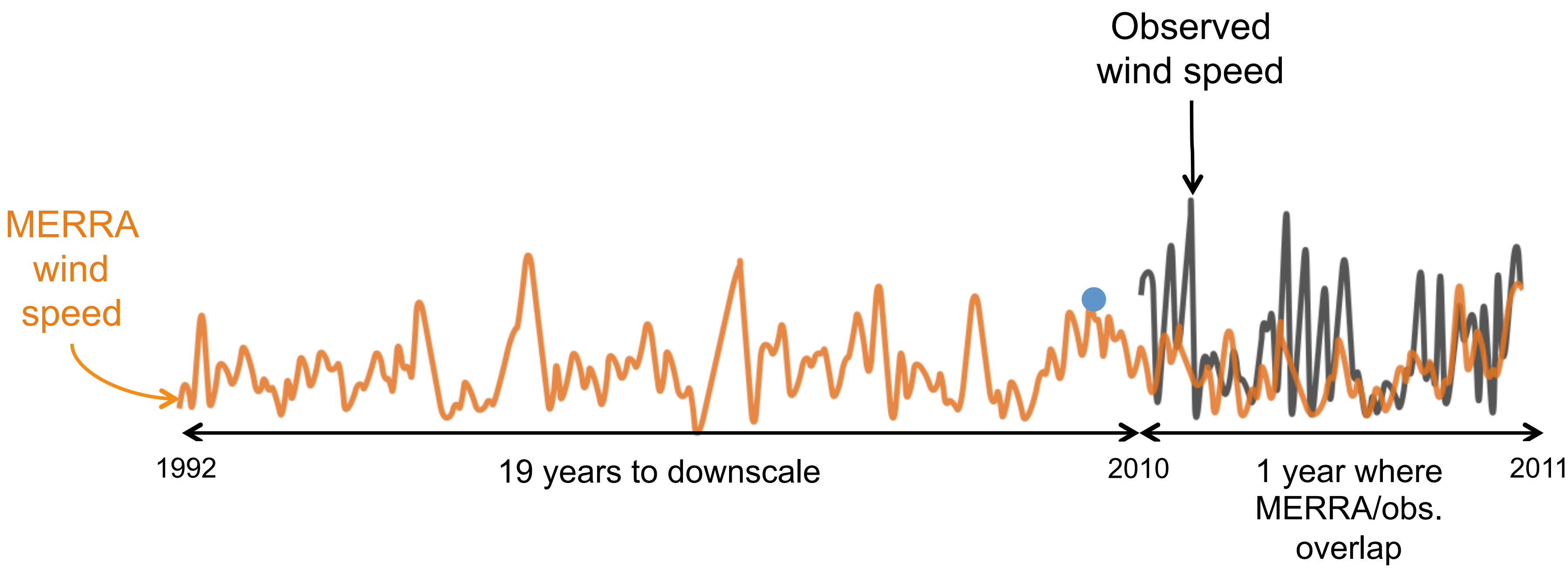

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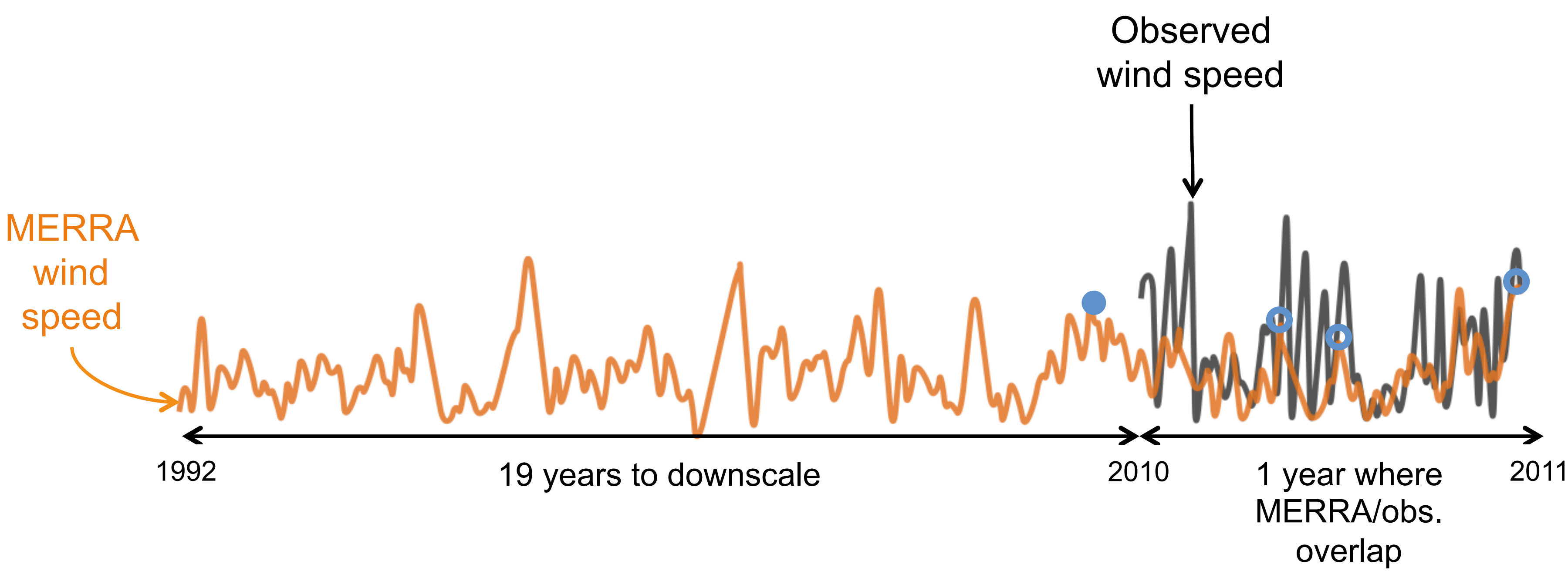

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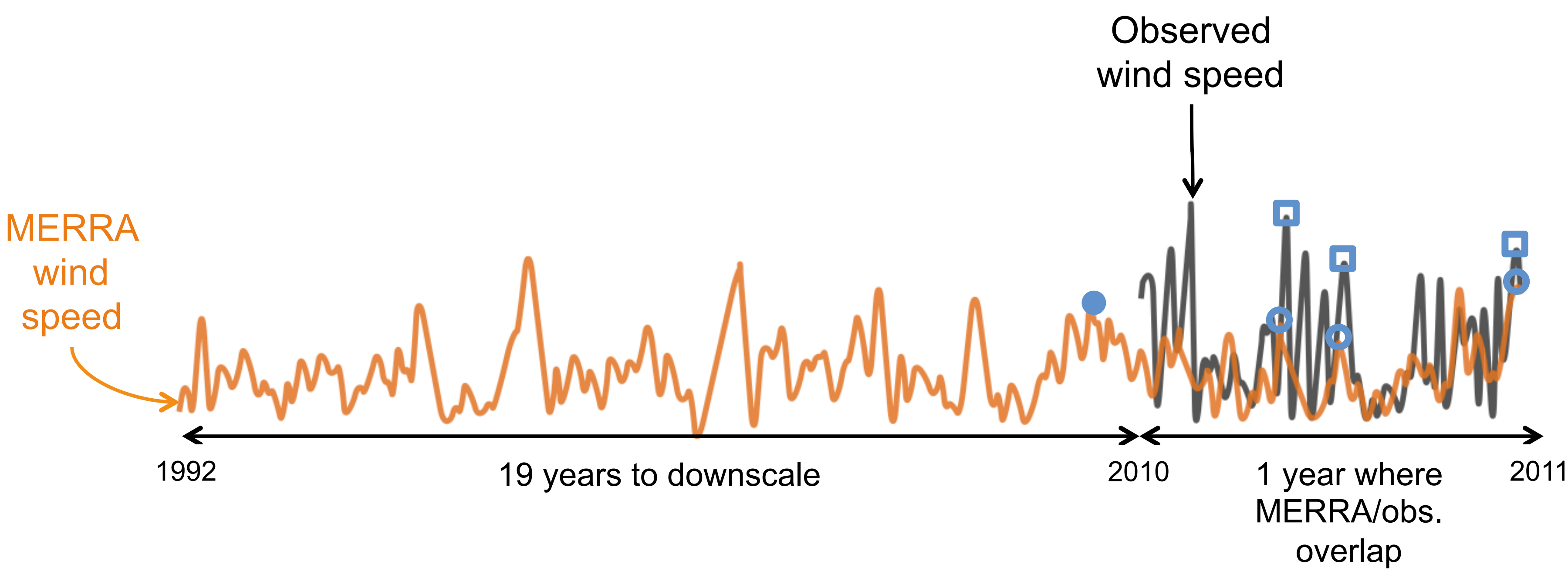

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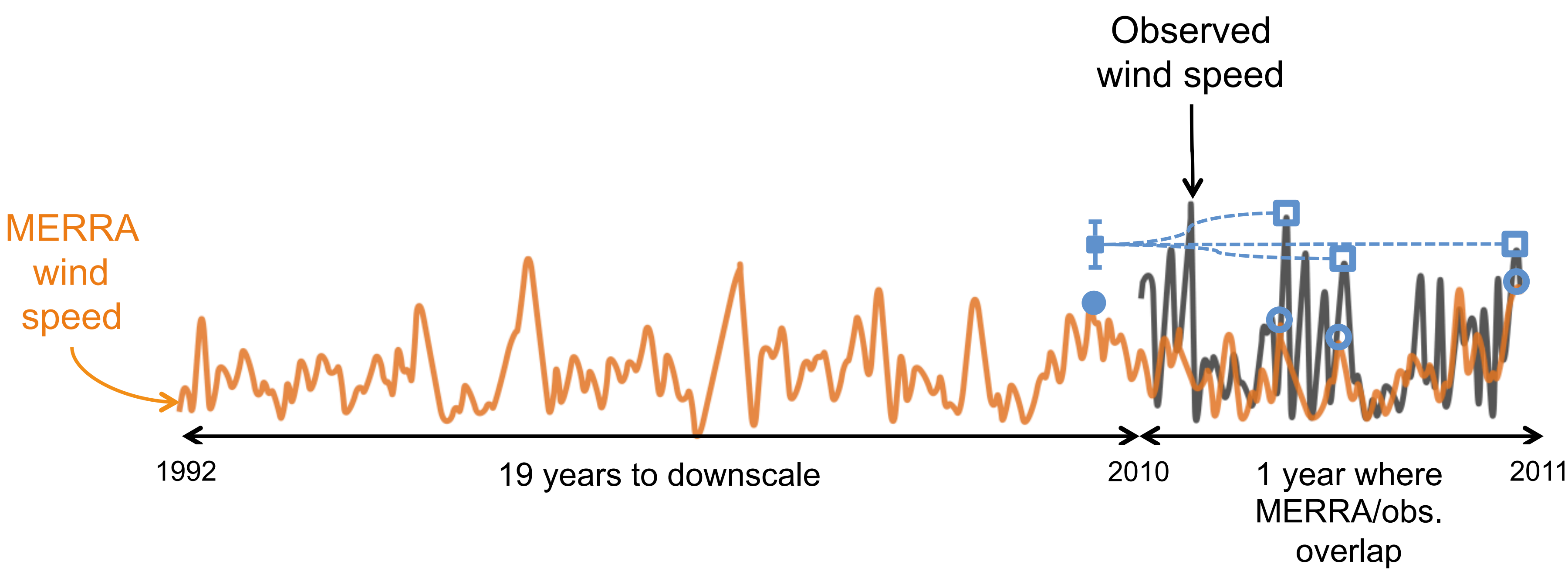

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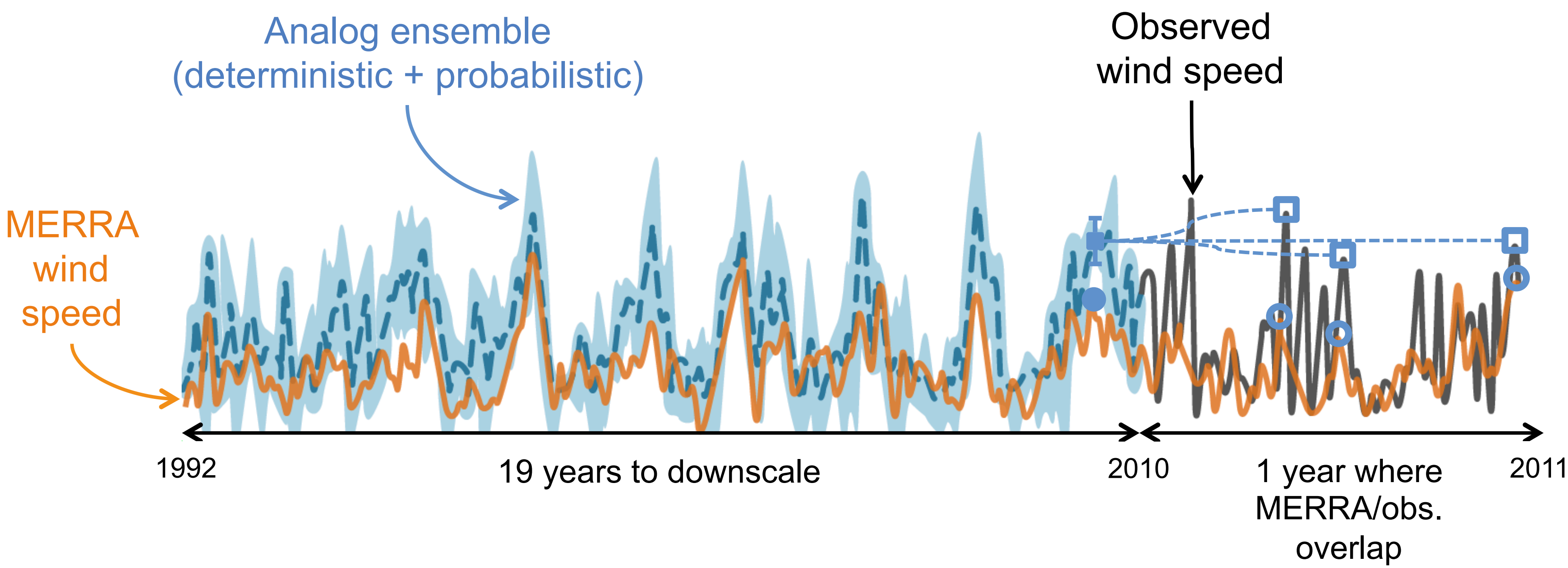
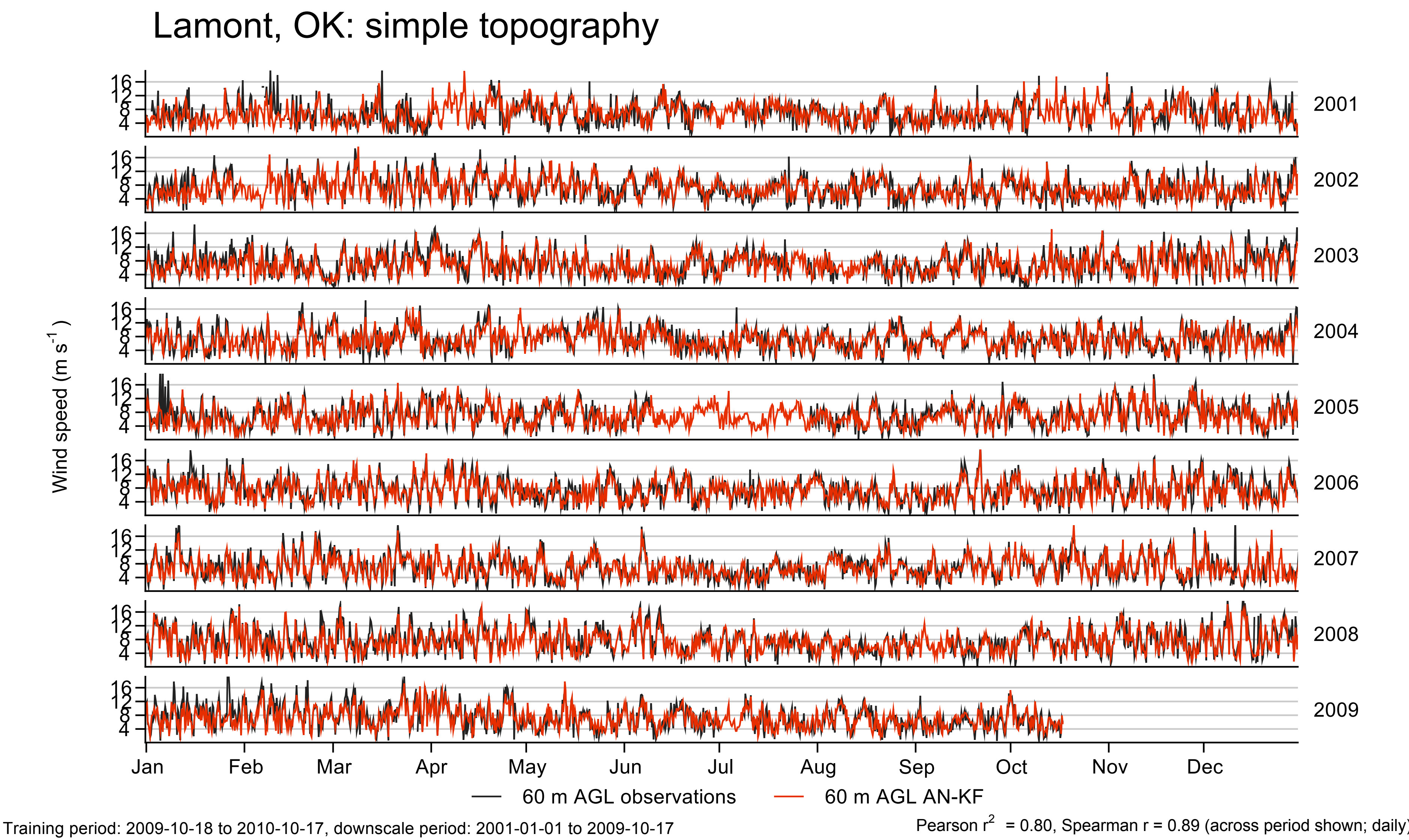
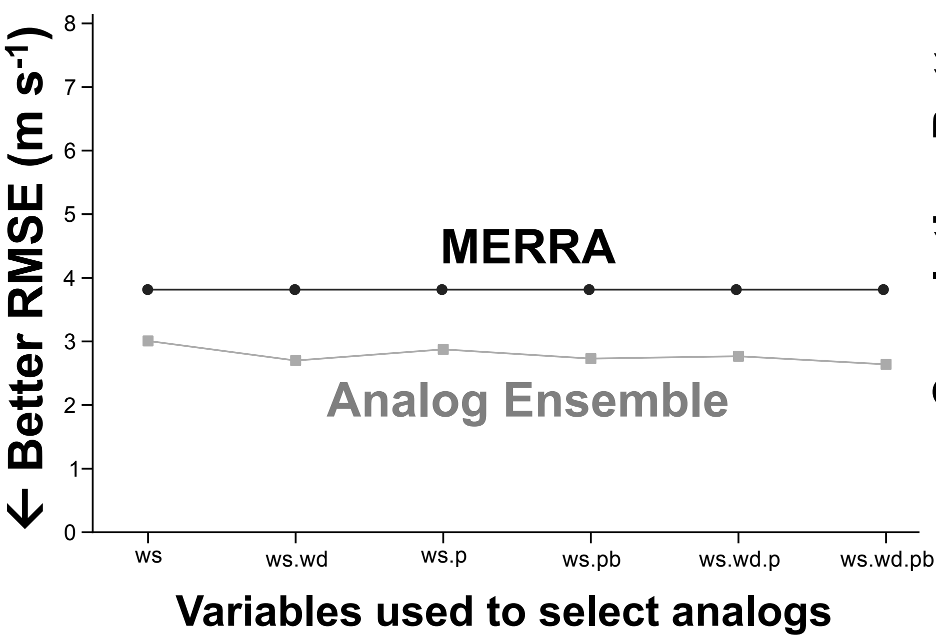


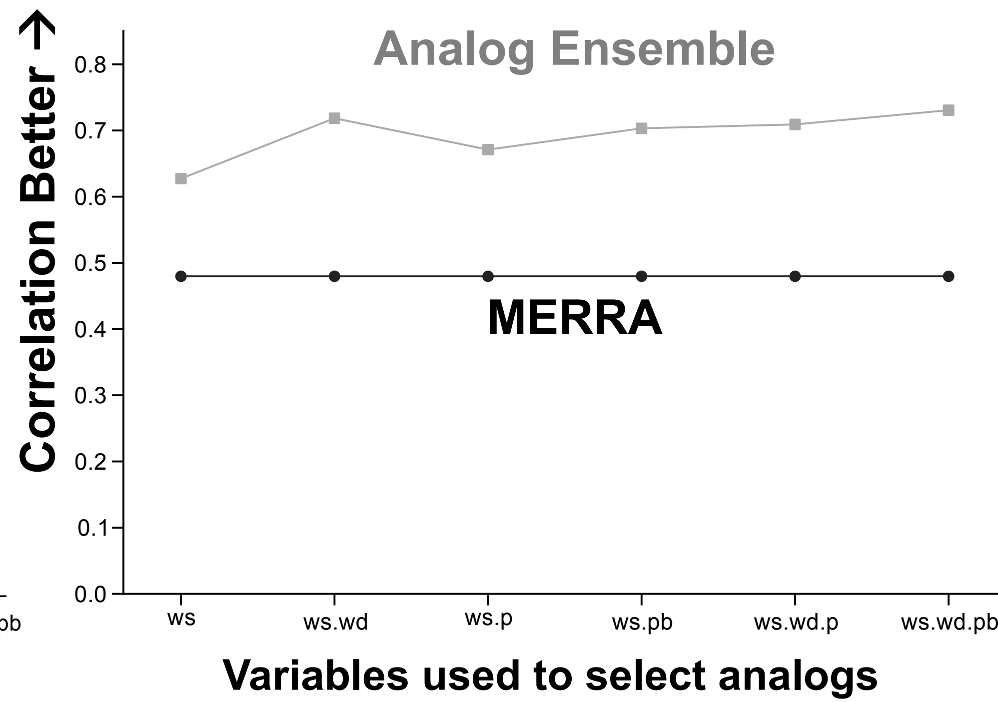
Results: example of time series (Lamont, OK)



Deterministic results (Lamont, OK)

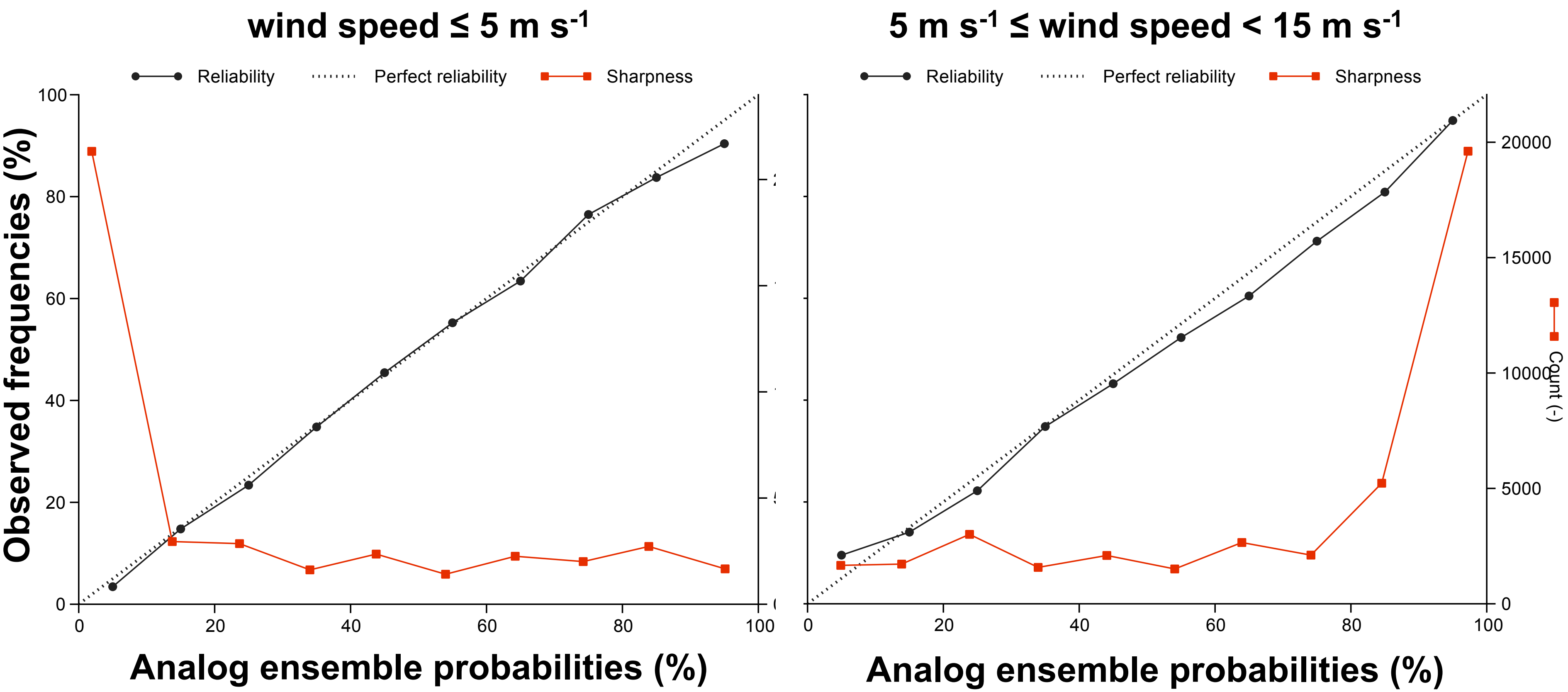
- **Analog ensemble better than MERRA**



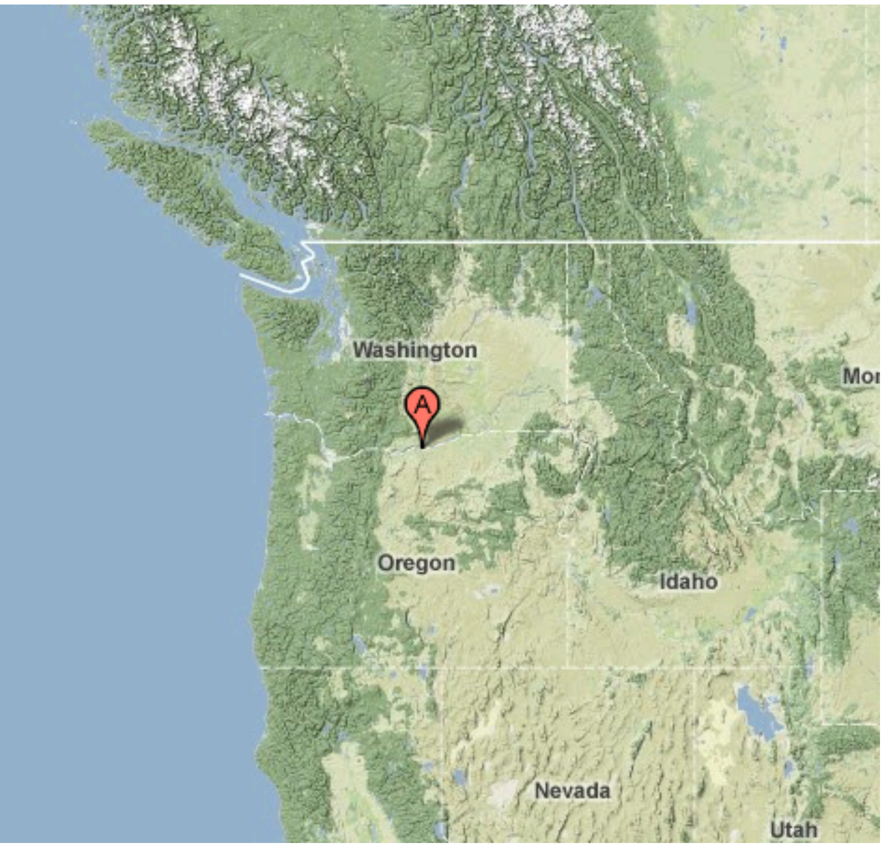


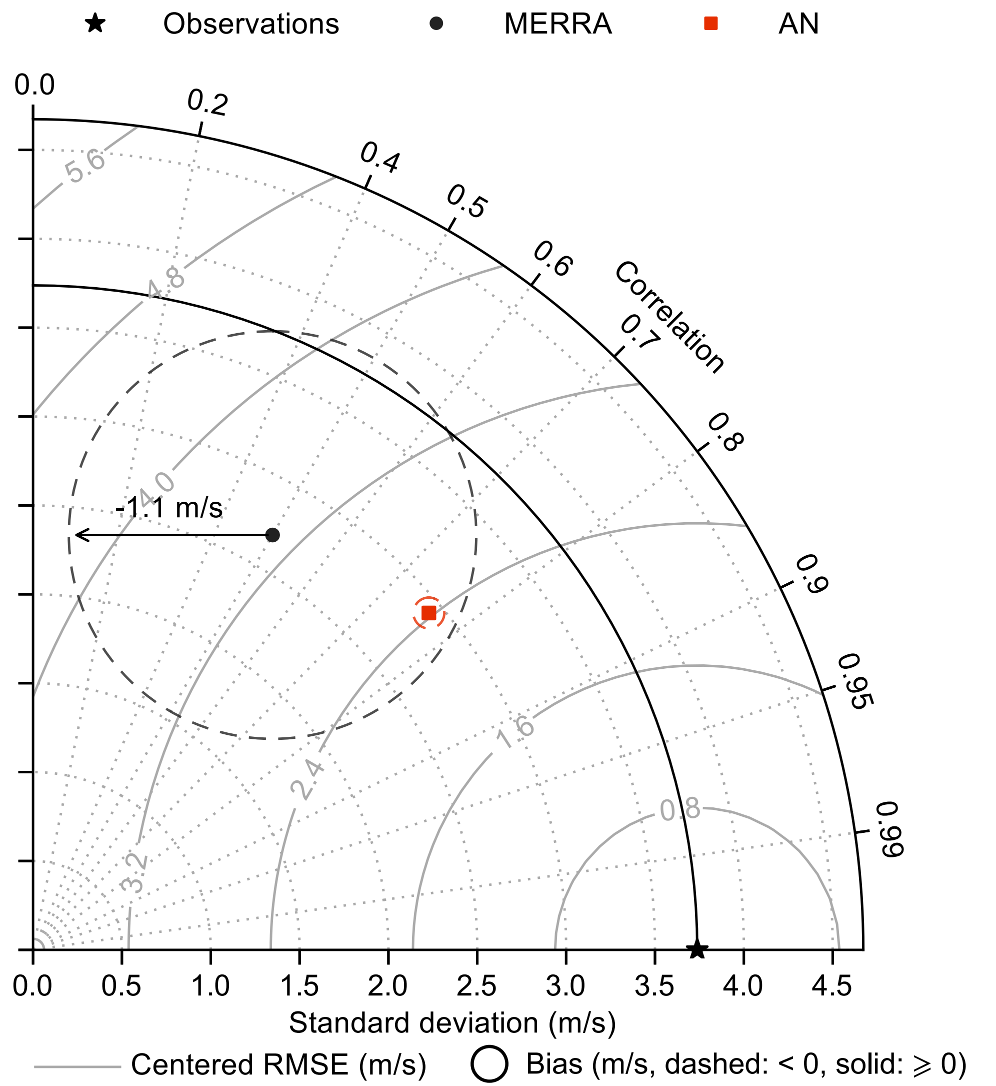
Probabilistic results (Lamont, OK)

- **Analog ensemble provides reliable uncertainty estimates**



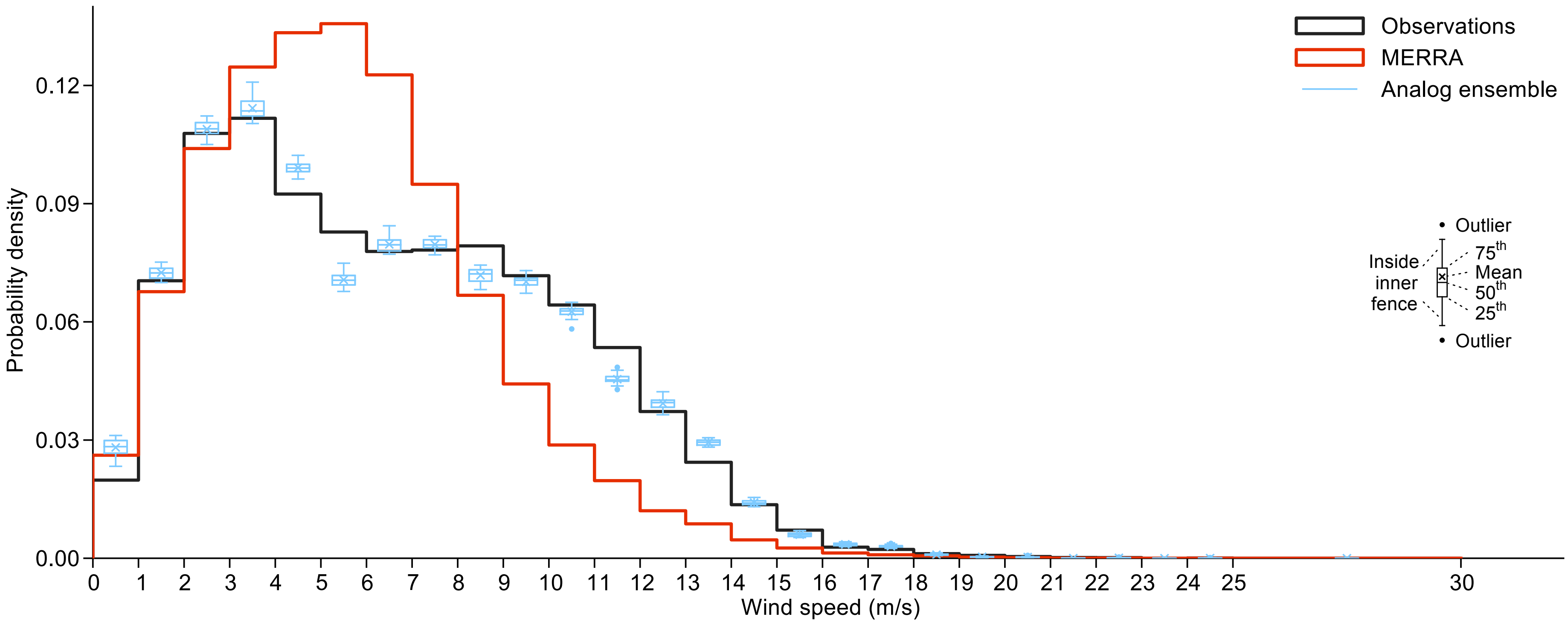
Deterministic results (Goodnoe Hill, WA)





Training period: last 365 days, period downscaled: last 5 entire years, analogs: 25

PDFs comparison (Goodnoe Hill, WA)



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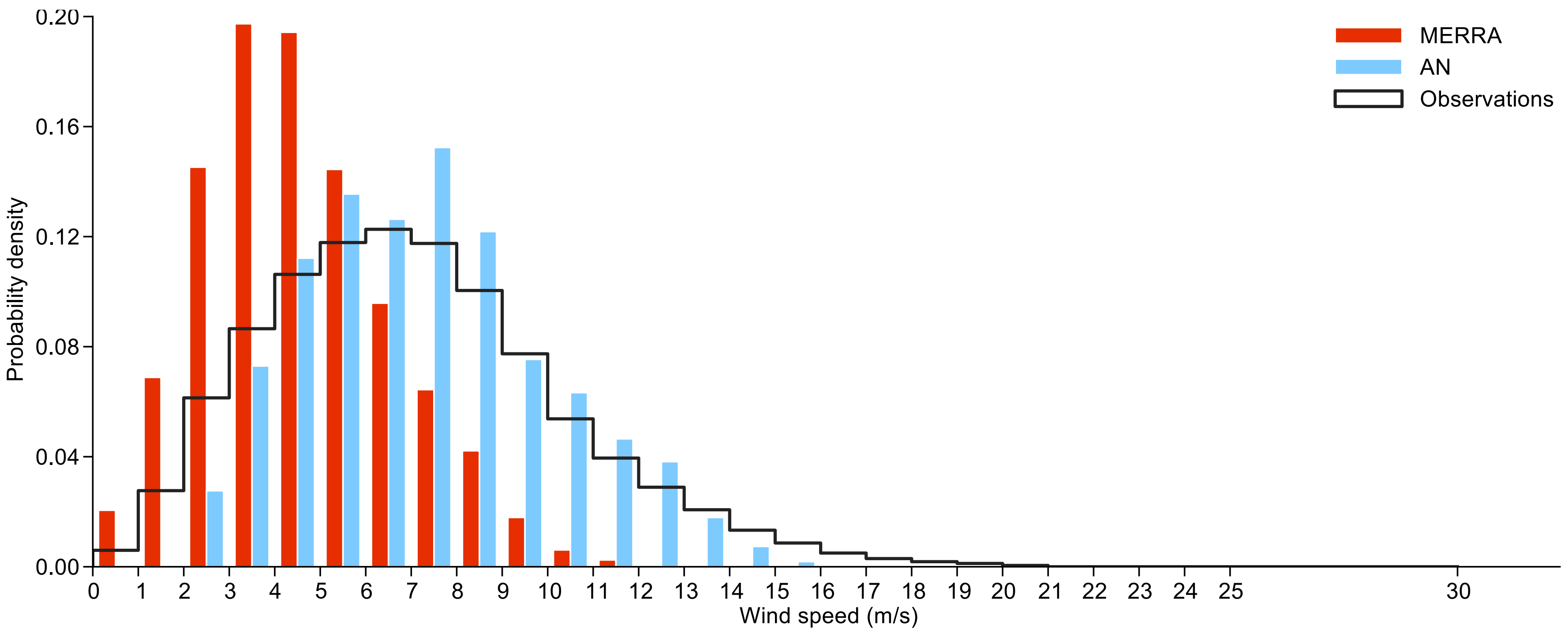
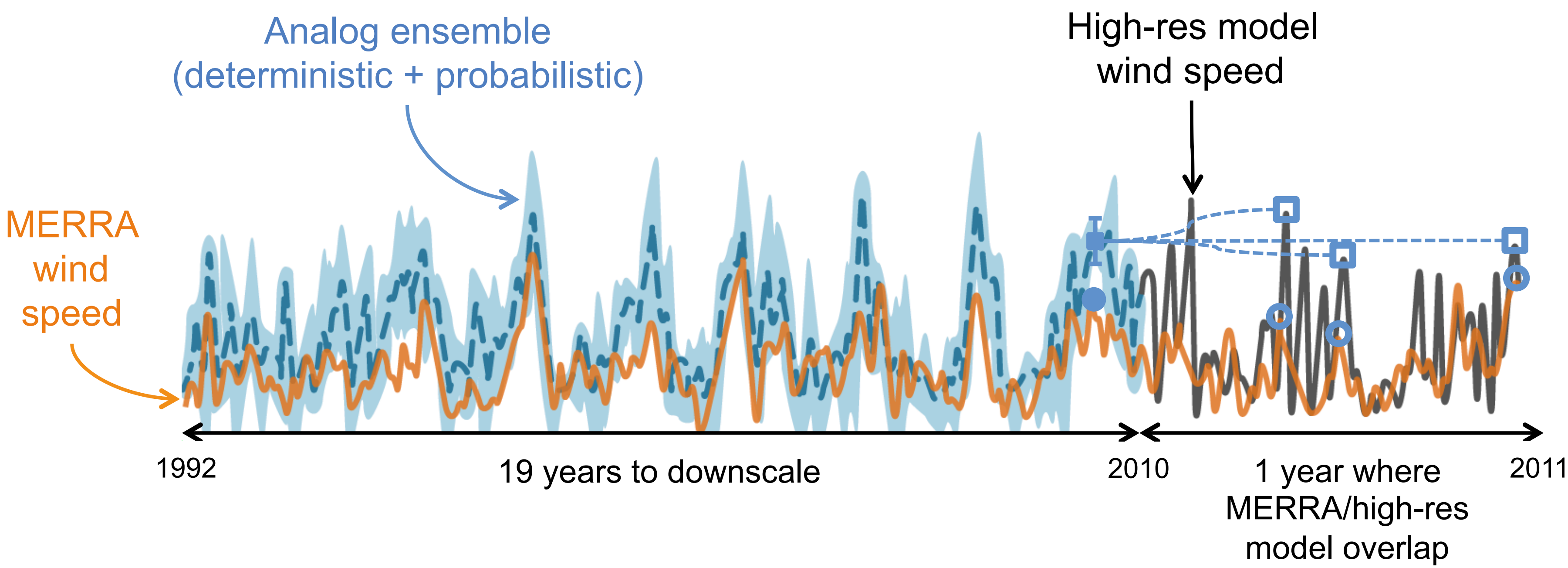
PDFs comparison ("Site 216")



Training period: last 365 days, period downscaled: last 3 entire years, analogs: 25

AnEn for wind resource assessment in areas with no observations

- Recreate a long-term observation-based wind climatology at site
- Downscale a long-term NASA Modern-Era Retrospective Analysis for Research and Applications (MERRA) time series using a short-term record from high-res model



Outline

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- Analog Ensemble (AnEn) basic idea
- AnEn for short-term (i.e., 0-48 h) weather predictions
- AnEn for short-term (i.e., 0-72 h) power predictions
- AnEn for long-term (i.e., multi-year) wind resource assessment
- Summary and future work

Summary and future work

- The analog ensemble provides accurate predictions/estimates and reliable uncertainty quantification (at a lower computational cost) for
  - Short-term (0-48 h) weather predictions
  - Short-term (0-72 h) power predictions
  - Long-term wind resource assessment
- The analog ensemble could also be used to drastically reduce the computational cost of dynamical downscaling (with the added value of uncertainty quantification)
- Could it be a game-changer for some of these applications?
- Current/Future work:
  - AnEn optimization (e.g., adaptive number of analogs)
  - Explore new predictors, and new predictor selection criteria
  - Tests with multi-year training data set

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Thanks!

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References:

- Delle Monache et al., 2011: Kalman filter and analog schemes to postprocess numerical weather predictions. *Monthly Weather Review*, **139**, 3554−3570.
- Delle Monache et al., 2013: Probabilistic weather predictions with an analog ensemble. Accepted to appear on *Monthly Weather Review*.
- Alessandrini, Delle Monache et al., 2013: Probabilistic power predictions with an analog ensemble. In preparation for *Applied Energy*.
- Nagarajan, Delle Monache et al., 2013: Performance of analog postprocessing methods across several variables and forecast models. In preparation for *Weather and Forecasting*.
- Vanvyve, Delle Monache et al., 2013: Wind resource assessment with an analog ensemble. In preparation for *Journal of Applied Meteorology*.

Estes Park, 2009

Research Applications Laboratory

Foote, Director — *Mahoney, Deputy Director* — *Hoswell, Lab Administrator*

Administration
Systems Admin
Multi-media

Staff are housed within the six Programs below, but work across projects in a matrix fashion

Aviation Appl. Program
Carmichael
Politovich/Barron

Hydromet Appl. Program
Rasmussen
Steiner/Blackburn

Wx Sys. & Assessment Prog.
Haupt
Drobot/Wiener

Nat'l DTC Director
Kuo

Nat'l Security Appl. Prog.
Swerdlin
Betancourt

Climate Sci. & Appl. Program
Buja
Miller

Joint Numerical Testbed
Brown
Nance/Carson

Projects

Aviation Appl. Program
- Icing
- Ceiling and visibility
- Dissemination of products
- Storm prediction
- Terrain-induced turbulence
- Turbulence
- Weather integration into decision making
- Winter weather

Nat'l Security Appl. Prog.
- Forecasting urban atmospheres
- High performance computing for operational systems
- Modeling hazardous plumes
- Mesoscale current-climate downscaling
- Operational NWP, improved data assimilation

Hydromet Appl. Program
- Hydrometeorological modeling
- Land-surface modeling
- Precipitation and aerosols
- Water and climate change
- Short-term storm forecasting

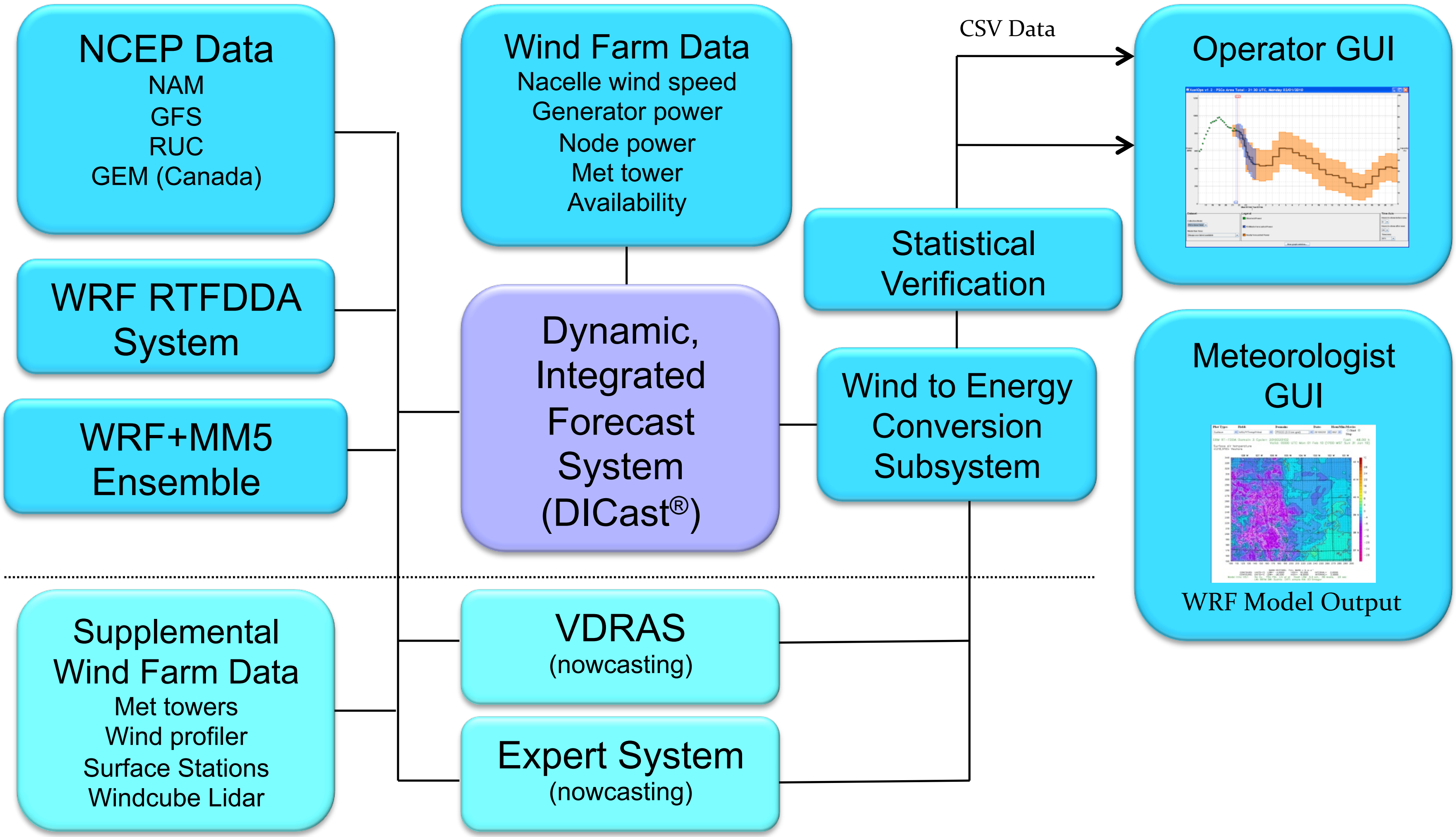
Climate Sci. & Appl. Program
- GIS science program
- Governance and adaptation
- Resilient and sustainable cities
- Regional adaptation to climate change
- Weather, climate, and health

Wx Sys. & Assessment Prog.
- International aviation weather
- Renewable energy
- Statistical prediction systems
- Surface transportation weather
- Use and value of weather information

Joint Numerical Testbed
- Advanced forecast evaluation methods
- Data assimilation testing
- Ensemble forecast evaluation
- Hazardous weather and hydromet testbeds
- Mesoscale model testing and evaluation
- Tropical cyclone testbed

Project Managers control the project budgets

NCAR's Wind Energy Prediction System for Xcel Energy



NCAR-Xcel Energy Project
Accurate prediction economical benefits

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~$1.9M per each percent improvement

2010 Total Benefit

- Error Reduction (expected 2%)
  - PSCo; NSP – much higher than expected
  - SPS – higher than expected
- Rate of Savings
  - PSCo – meets expectations (expected $800k/%MAPE)
  - NSP – higher than expected (expected $500k/%MAPE)
  - SPS – much lower than expected (expected 600k/%MAPE)

OpCo	2009	2010	Delta	Rate of Savings	Annualized
PSCo	18.07%	14.25%	-3.81%	$ 850,665	$ 3,245,102
NSP	15.66%	12.20%	-3.47%	$ 748,827	$ 2,596,873
SPS	16.26%	13.86%	-2.39%	$ 175,000	$ 418,443

*Mean Absolute Percent Error

Wind Forecasting Savings	**$ 6,260,417**
Curtailment Auditing Savings	**$ 1,260,000**
Grand Total	**$ 7,520,417**

Xcel Energy

NCAR-Xcel Energy Project
CO_2 reduction due to accurate predictions

"The avoided generation occurred when Xcel cycled offline baseload thermal units (coal or natural gas combined cycle) due to extended periods of forecasted low loads and high winds."

AVOIDED EMISSIONS DUE TO IMPROVED PREDICTIONS: 238,136 TONS OF CO_2

MWh's of avoided generation in 2011
Arapahoe 3 = 317
Arapahoe 4 = 6,941
Cherokee 1 = 11,606
Cherokee 2 = 13,772
Valmont 5 = 10,061
FSV CC = 93,626
RMEC CC = 308,989

Probabilistic forecast attributes: Economic value (value score)

Potential value of a forecast in a decision making framework; it can be estimated using a static cost-loss decision model for a dichotomous event (Wilks, 2006).

A decision maker can chose to pay a cost C (e.g., cost of evacuation efforts) to protect against a possible loss L (with L > C): if protective action is not taken, than the decision maker incurs a loss L if the adverse event incurs (e.g., lost lives).

Analysis of Value

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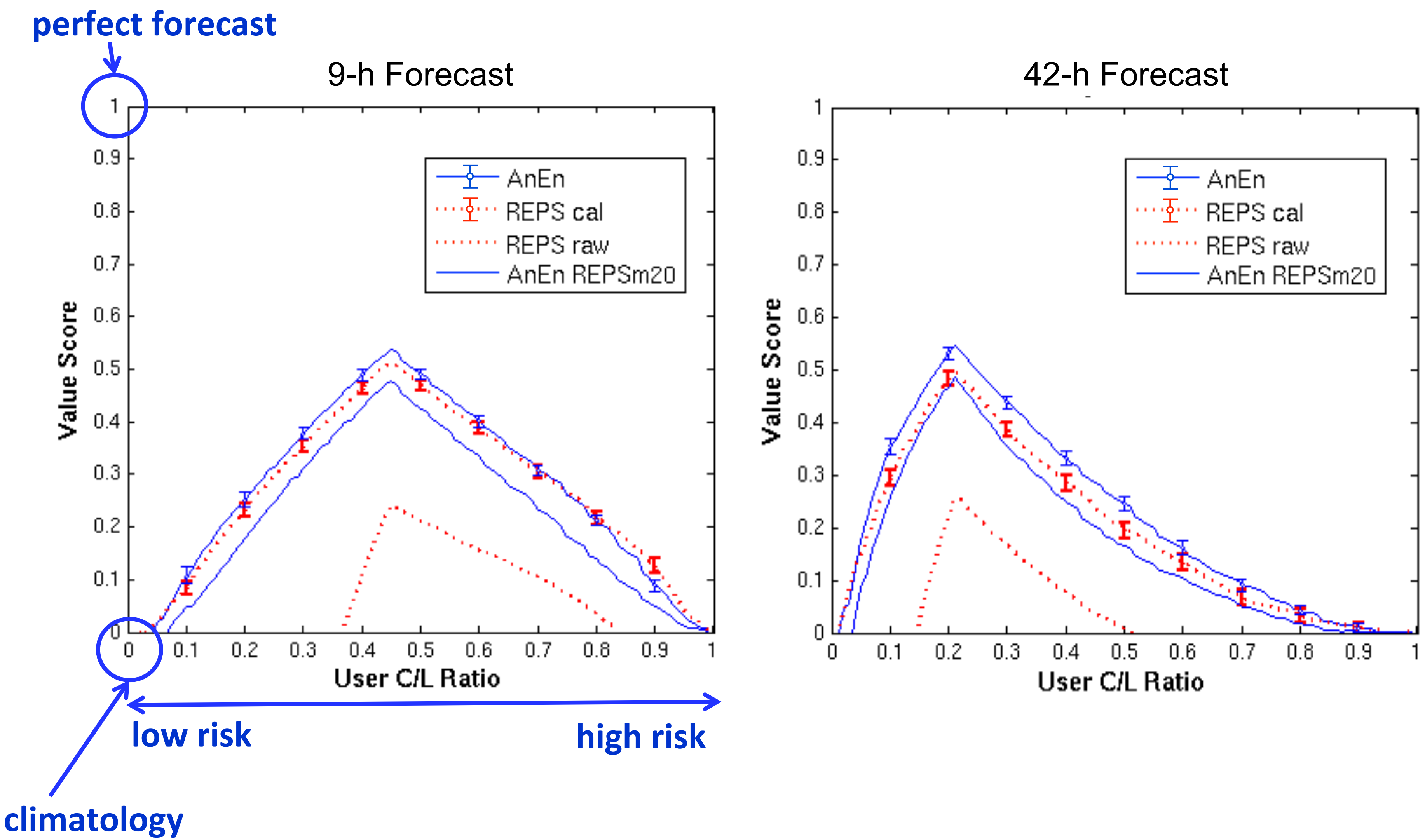
Economic value diagram, 10-m wind speed ≥ 5 m/s



Analysis of spread-error consistency (1)

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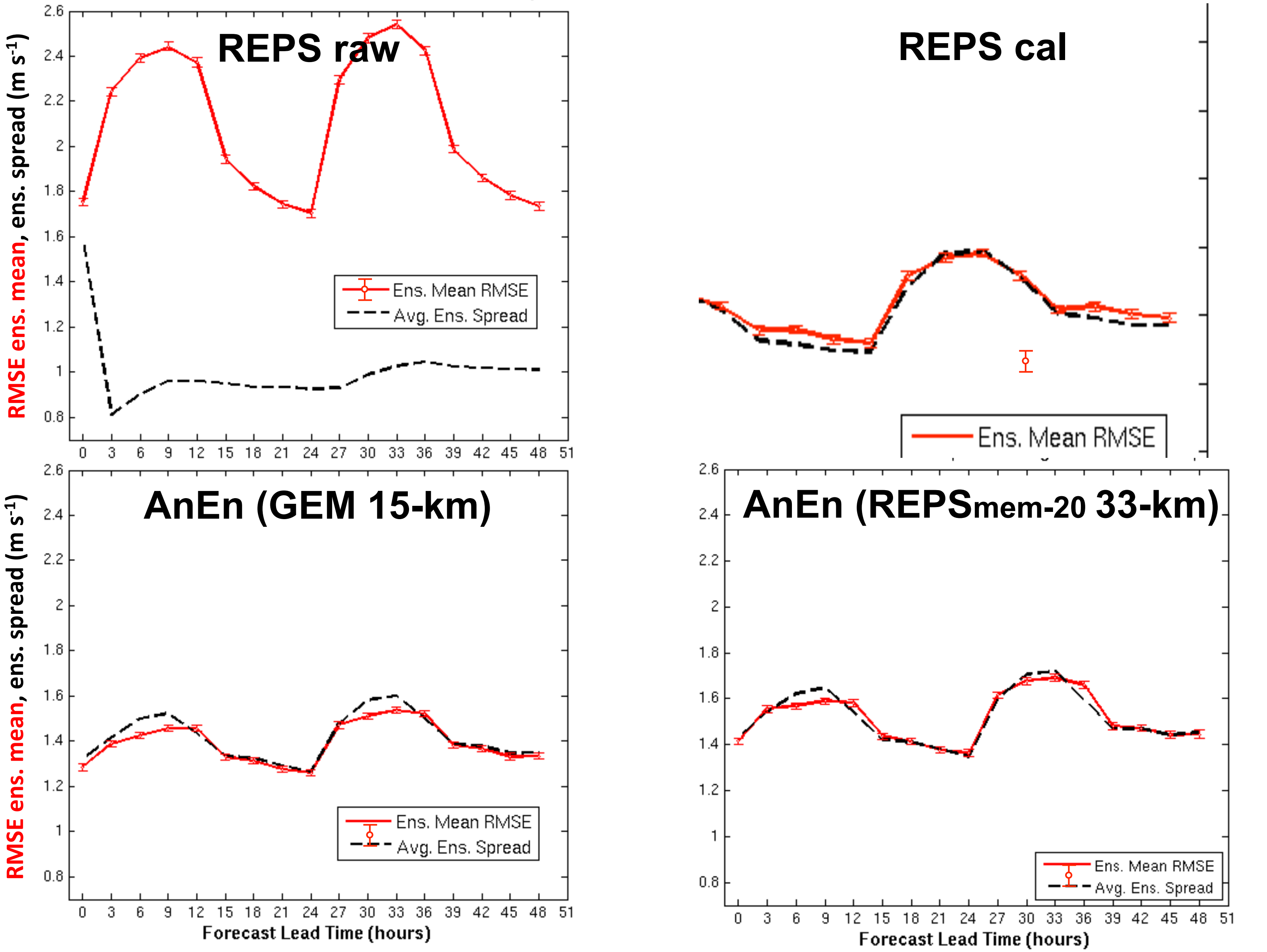
Dispersion diagram for 10-m wind speed



Measuring Value

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Value Score *(or expense skill score)*

$$VS = \frac{E_{fcst} - E_{clim}}{E_{perf} - E_{clim}}$$

E_{fcst} = Expense from follow *the* forecast

E_{clim} = Expense from follow a climatological forecast

E_{perf} = Expense from follow a perfect forecast

$$VS = \frac{\frac{1}{M}(a\alpha + b\alpha + c) - \min(\alpha, \bar{o})}{\bar{o}\alpha - \min(\alpha, \bar{o})}$$

a = # of hits

b = # of false alarms

c = # of misses

d = # of correct rejections

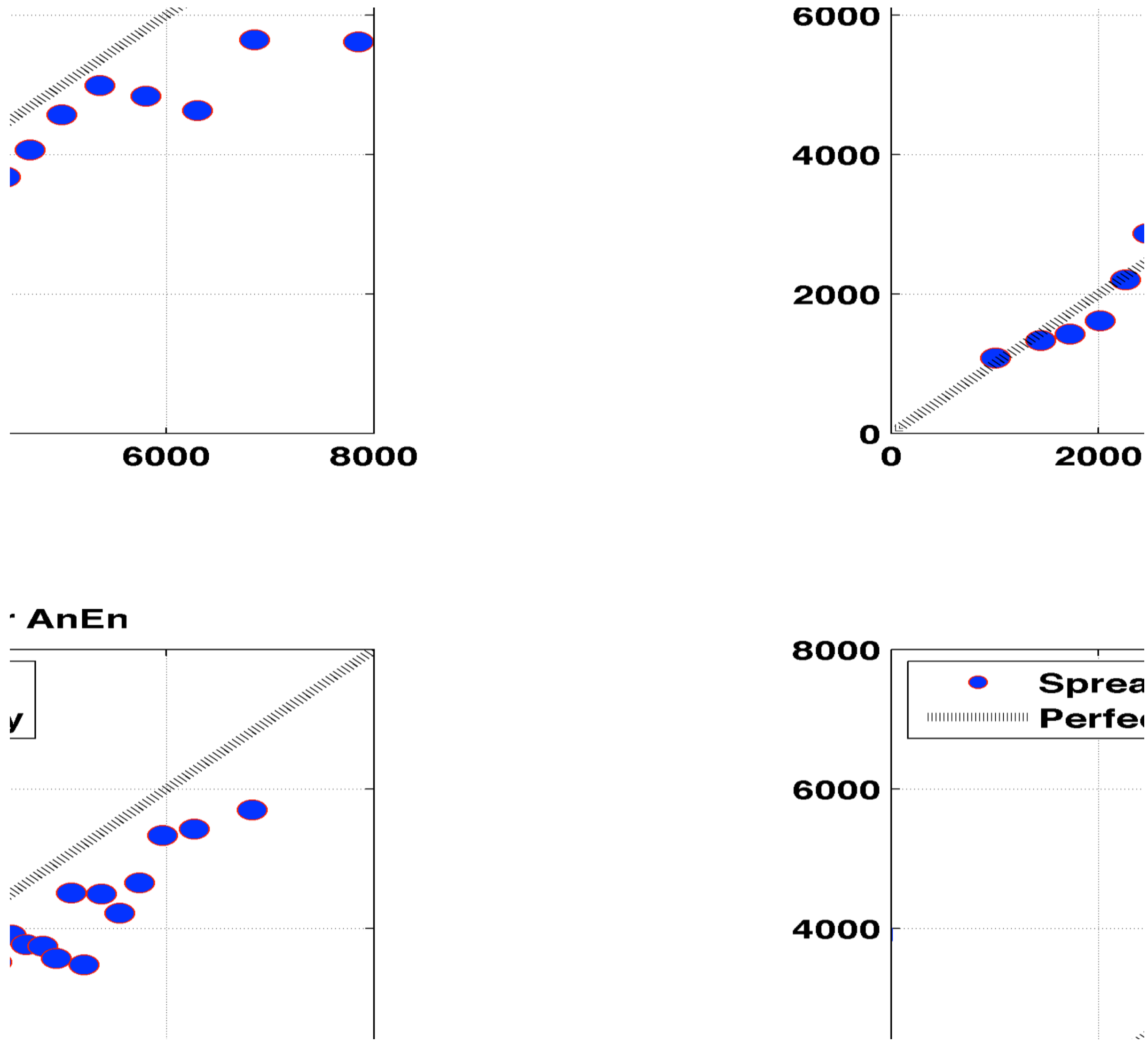
α = C/L ratio

$\bar{o}$ = $(a+c) / (a+b+c+d)$

Forecast and/or Prepare		Event Observed: Yes	Event Observed: No
	Yes	*a*	*b*
	No	*c*	*d*

Power predictions (2)

Binned spread-skill diagram, power forecasts



The metric (1)

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Analog strength for a particular forecast lead time *t* is measured by the distance between current and past forecast, over a short window, $2\tilde{t}$ wide

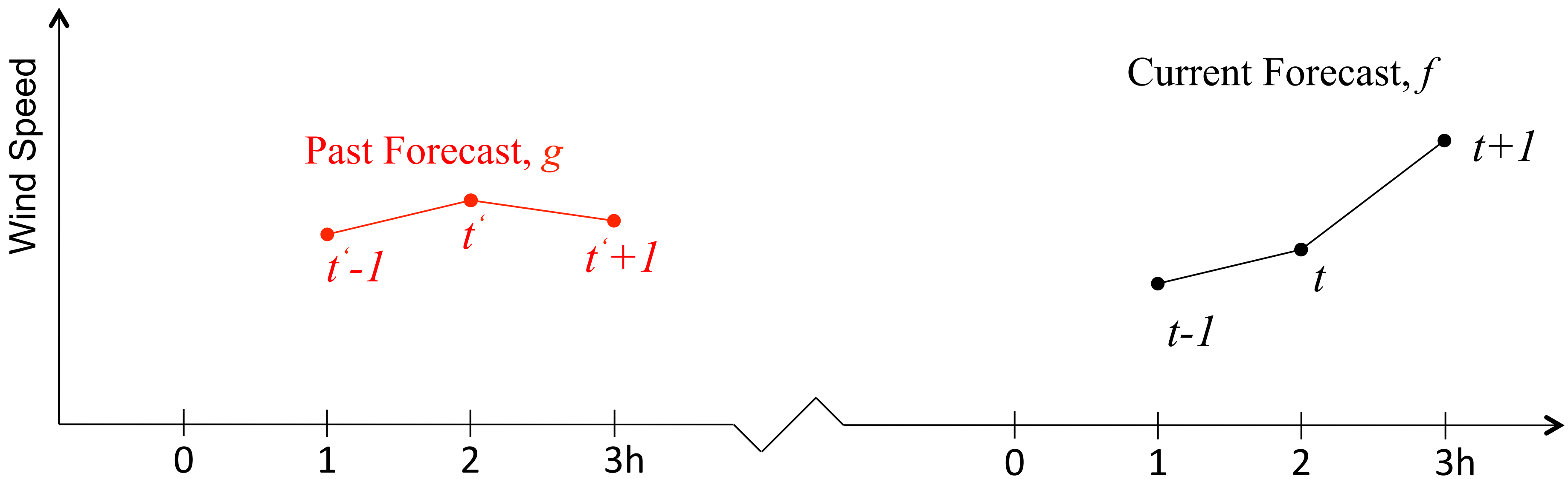
$$\left\| f_t - g_{t'} \right\| = \frac{1}{\sigma_f} \sqrt{\sum_{k=-\tilde{t}}^{+\tilde{t}} \left(f_{t+k} - g_{t'+k} \right)^2}$$

σ_f : Forecasts' standard deviation over entire analog training period

Expanded to multiple predictor variables, but still focused on predictand f:
(for wind speed, predictors are speed, direction, sfc. temp., sfp pressure, and PBL depth)

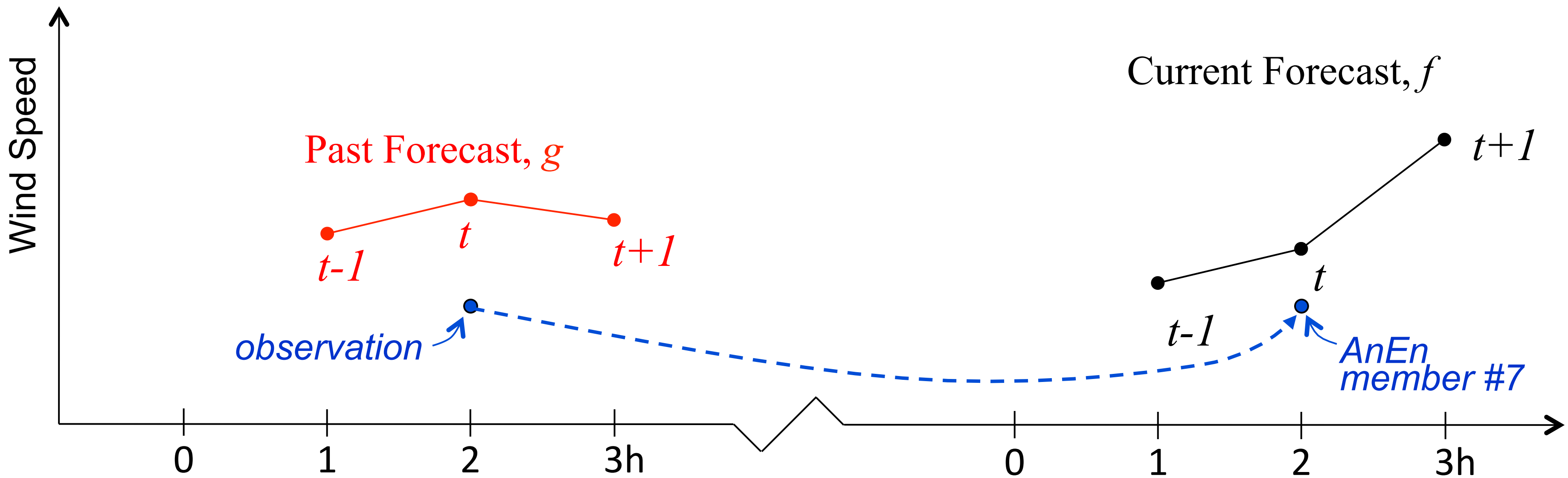
$$\left\| f_t - g_{t'} \right\| = \sum_{v=1}^{N_v} \frac{w_v}{\sigma_{f^v}} \sqrt{\sum_{k=-\tilde{t}}^{+\tilde{t}} \left(f^v_{t+k} - g^v_{t'+k} \right)^2}$$

N_v : Number of predictor variables
w_v : Weight given to each predictor



The metric (2)

After finding the n strongest analogs, each of the n AnEn members is taken as the verifying observation from each analog.

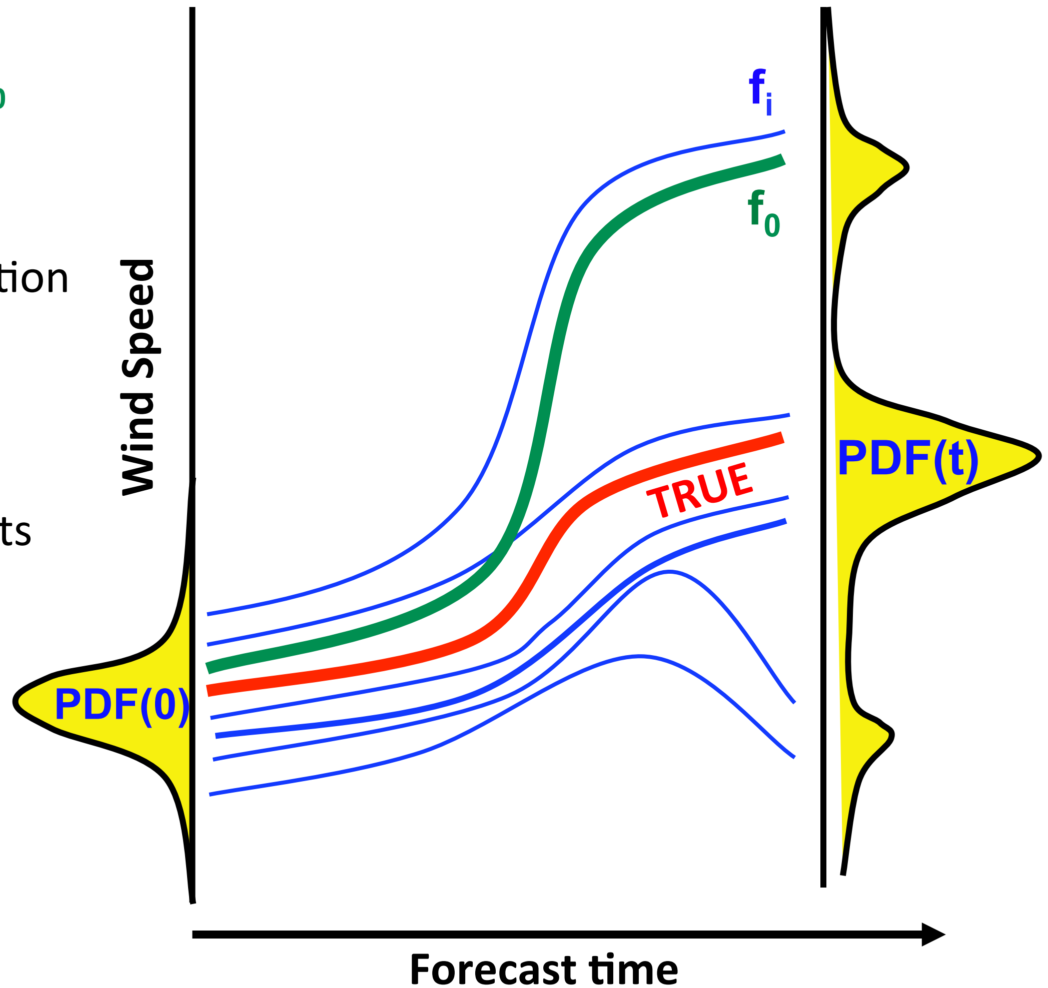


Ensemble Prediction

The single deterministic forecast f_0 fails to predict the **TRUE**

The initial probability density function **PDF(0)** represents the initial uncertainties

An ensemble of perturbed forecasts f_i, starting from perturbed initial conditions designed to sample the initial uncertainties can be used to estimate the probability of future states **PDF(t)**



Cost-benefit of the analog technique (1)

- Design, implementation, and maintenance of the analog and NWP ensemble techniques
  - Shared requirements
    - NWP-model-based data assimilation and forecast.
    - Calibration: both approaches use a calibration technique, and each requires about the same effort to develop and implement
  - Unique requirements for REPS
    - Multiple physics packages (for multimodel ensembles), and
    - Stochastic physics routines

Cost-benefit of the analog technique (2)

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- Computational expense
  - <u>SCENARIO I</u>: You must run your own NWP model
    - REPS requires about 2-3 times more calculations than the analog technique
  - <u>SCENARIO II</u>: Use an available NWP product (e.g., from NCEP)
    - REPS requires <u>orders of magnitude more calculations</u> than the analog technique

NASA's MERRA

- Introducti
on

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- NASA Modern-Era Retrospective Analysis for Research and Applications (MERRA)
    - Based on NASA's Global Atmospheric Model and Data Assimilation System
    - 3-D worldwide record of weather from 1979
    - 1/2 degrees latitude × 2/3 degrees longitude
    - Hourly surface 2D and 6 hourly 3D fields
    - Assimilation of all NASA historical satellite data
    - Conventional data